# Star formation

Physics and Chemistry of the Interstellar Medium

# Starting point

- Stars from through gravitational collapse of dense interstellar clouds of gas and dust

- The physics and chemistry of those molecular clouds governs the star-formation process

# Historical approach to the ISM

*1781* — *Charles Messier (1730-1817) publiziert einen Katalog von Nebeln und Sternhaufen (M42 - Orion Nebel, M31 - Andromeda Nebel).*

*~1800* — *William Herschel publiziert einen Katalog von Nebeln („Löcher im Himmel“ - sternleere Gebiete).*

*1814 - 1920 Entwicklung der Spektroskopie als Grundlage der Astrophysik*

*1814* — *Sonnenspektrum durch Fraunhofer (1787-1826)*

*1859* — *Identifikation der Spektrallinien durch Bunsen & Kirchhoff*

*1861* — *Identifikation der Elemente im Sonnenspektrum durch Kirchhoff*

*1864* — *Spektren von M31 (sonnenähnlich) und M42 (Emissionslinien) durch William Huggins*

*1904* — *Hartmann findet stationäre CaII Absorptionslinien im Spektrum des spektroskopischen Doppelsterns $\delta$ Orionis.*

*1913* — *Entdeckung der Höhenstrahlung durch Hess*

*1919* — *Barnard veröffentlicht einen Katalog von Dunkelwolken.*

*1927* — *Clay findet, daß Höhenstrahlung durch hochenergetische geladene Teilchen verursacht wird.*

*1928* — *Bowen identifiziert die vorher einem Element „Nebulium“ zugeordneten Linien als Übergänge metastabiler Niveaus von [NII], [OII] und [OIII], die durch $e^-$-Stöße angeregt werden.*

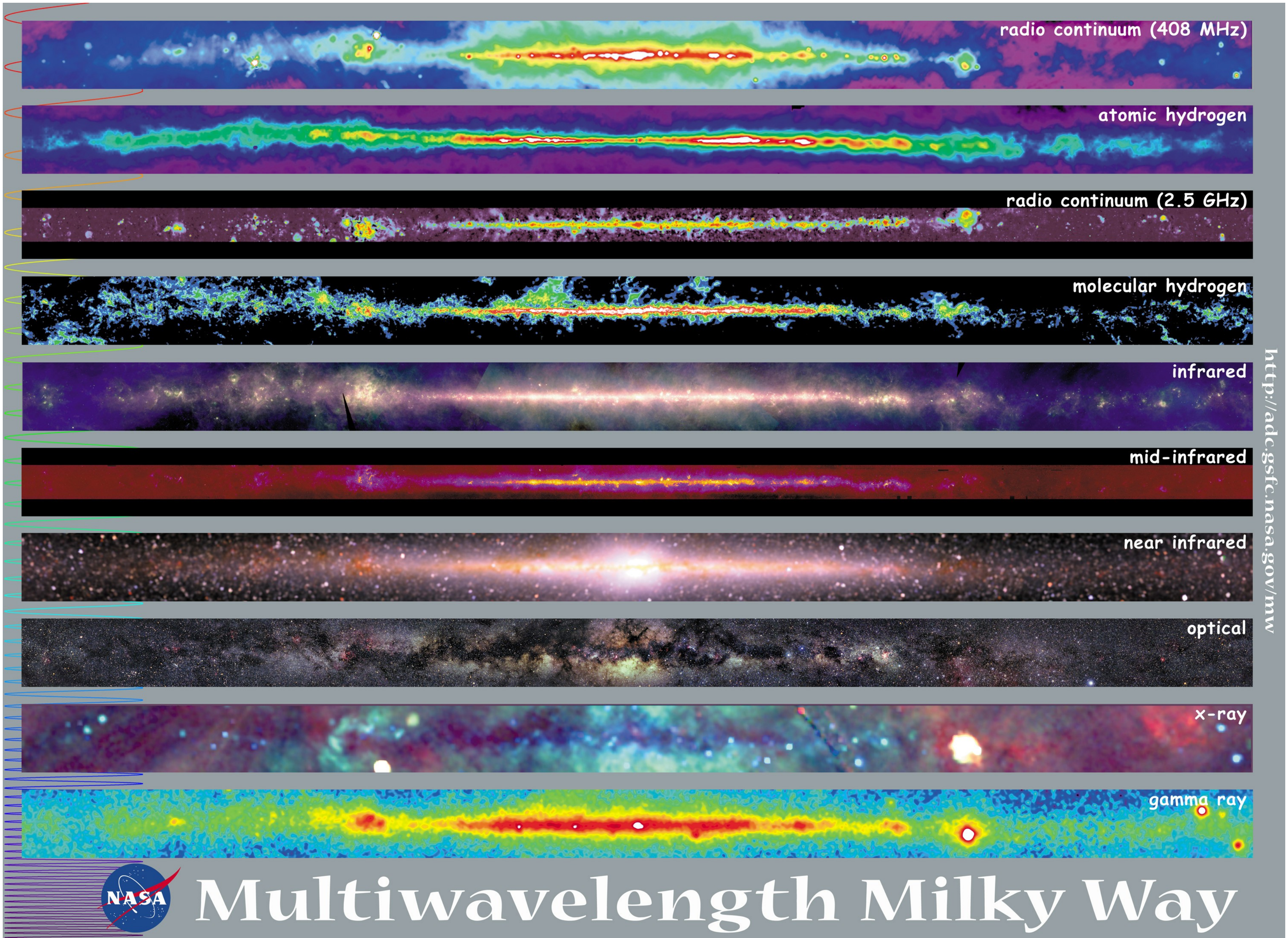
# Historical approach to the ISM

| | |
|---|---|
| *1930* | *Robert Trümpler (1886-1956) stellt fest, daß entferntere Sternhaufen größer und heller erscheinen -> interstellare Extinktion* |
| *1933* | *Plaskett & Pierce weisen die Existenz des interstellaren Mediums zweifelsfrei nach: CaII Linien sind stärker bei entfernteren Sternen* <br> *Radialgeschwindigkeit $v_{CaII}$ der Linien etwa $v_*/2$* |
| *1934* | *Entdeckung der „Diffusen interstellaren Banden“ (DIBs) durch Merrill* |
| *1937* | *Entdeckung der ersten interstellaren Moleküle (CH, $CH^+$, CN) durch Swings & Rosenfeld, Mc Kellar und Adams* |
| *1945* | *Vorhersage der 21cm Strahlung von neutralem Wasserstoff durch van de Hulst* |
| *1950* | *Nachweis dieser Linie durch Ewen & Purcell und Oort & Müller* <br> *Identifikation von Protonen und $\alpha$ Teilchen als Bestandteile der kosmischen Strahlung* |
| *1960* | *Entdeckung der weichen Röntgen-Strahlung von heißem ionsierten Gas* |
| *1963* | *Barrett, Meeks & Weinreb entdecken OH anhand von Absorptions- und Emissionslinien (Maser) bei 18 cm* |
| *1968* | *Nachweis des ersten polyatomaren Moleküls ($NH_3$) durch die Gruppe von Charlie Townes* |

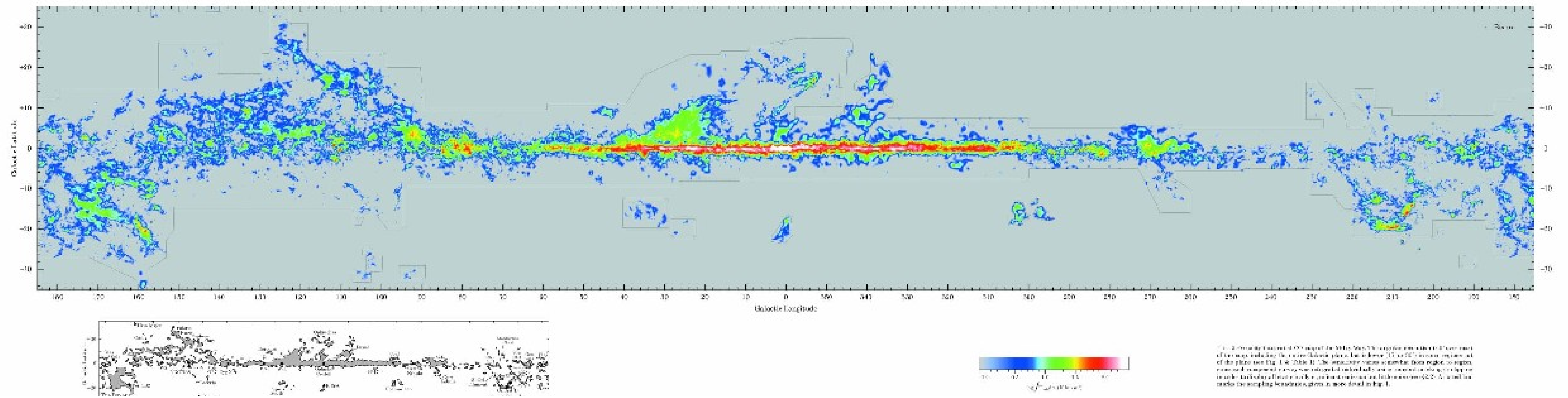
# Historical approach to the ISM

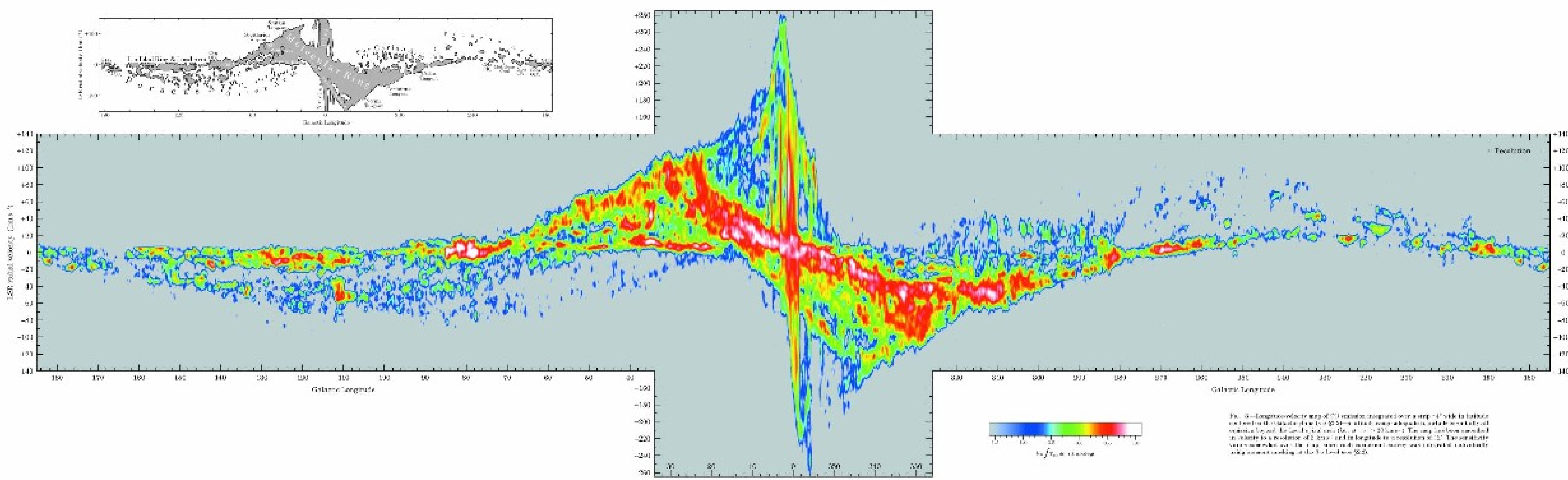
| | |
|---|---|
| *1970* | *Nachweis der Emission des Rotationsübergangs J=0-1 von CO bei 2.6 mm (115 GHz) durch Wilson, Jefferts & Penzias* |
| | *Radionachweis z.T. „exotischer" Moleküle, Kartierung der CO-Emission der Milchstraße* |
| | *Entdeckung von $H_2$-Linien im ultravioletten Spektralbereich durch Carruthers* |
| *1973* | *Copernicus UV-Satellit: Entdeckung einer sehr heißen Komponente des interstellaren Mediums anhand hochionisierter Atome (z.B. O VI)* |
| | *Verringerung der chemischen Häufigkeit von Elementen in der Gasphase durch „Abreicherung" auf Staubteilchen* |
| *1980* | *Entwicklung der Infrarot-Astronomie:* |
| | *Entdeckung von $H_2$-Linien, Festkörper- und Eis-Banden* |
| | *Himmelskartierung durch IRAS* |
| | *Anzeichen für sehr kleine Staubteilchen und große Moleküle* |
| | *Entwicklung der Submm-Astronomie:* |
| | *Untersuchung der warmen Grenzgebiete zwischen HII-Regionen und Molekülwolken (Photon dominated regions - PDRs)* |
| | *Suche nach kalten protostellaren Objekten* |
| *1995* | *ISO-Satellit: $H_2O$ in Sternenstehungsgebieten, Chemie des Staubes, $H_2$* |
| *1995* | *SIRTF-Satellit: Durchmusterung der Milchstraße, Scheiben und Planetenentstehung* |

# Our Galaxy seen at different wavelengths



# Milky Way in CO



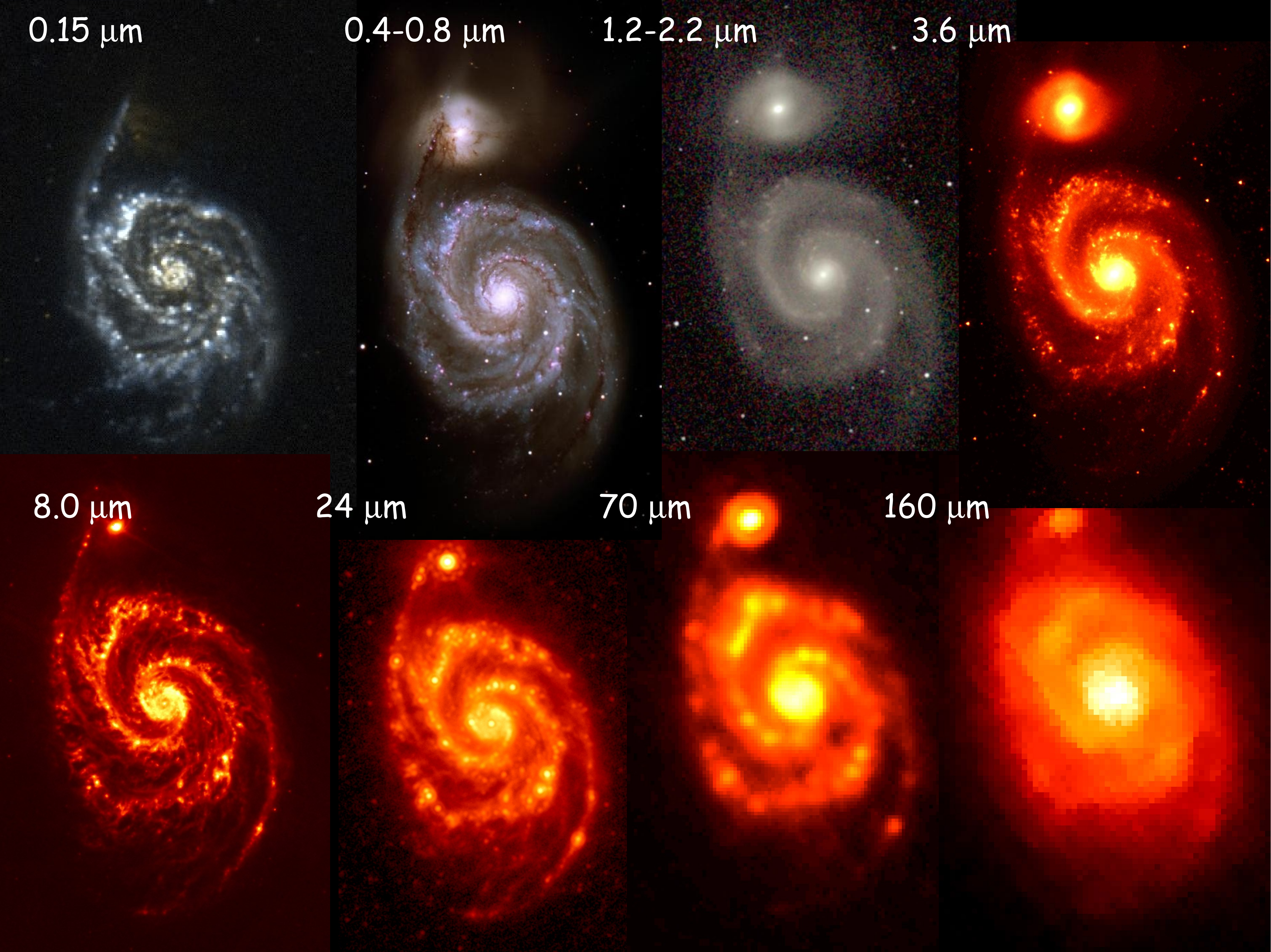
# Molecular Cloud formation

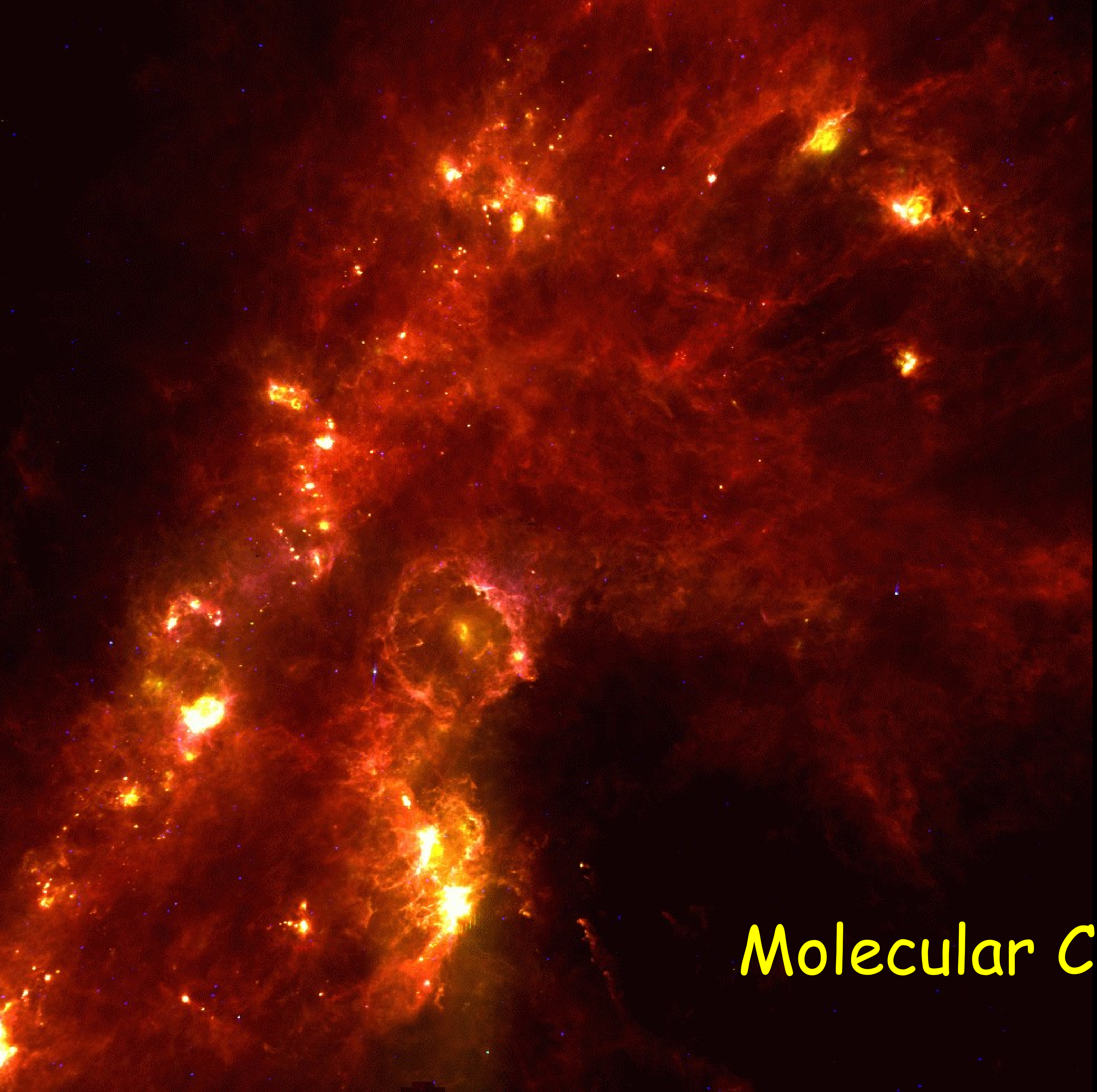
FIG. 5.—Section of the southern inner arm of M51 from the full-resolution Hubble Heritage image. The overall dimensions are 3.49 by 1.65 kpc. There are two giant cloud complexes in the main dust lane ($10^7\ M_\odot$). Each has embedded H II regions, showing that star formation begins very soon after cloud formation with no significant downstream displacement. The postshock flow is mostly from left to right in this figure as the gas streams along the spiral arm. The feathers of dust clouds below the main dust lane are twisted remnants of former cloud complexes in which star formation has dispersed the cores. Many filaments or ribbons of dust surround complexes of bright blue stars, suggesting pressurized dispersal. Star formation lingers in the filaments and in other debris because of triggering from these pressures and because of parallel collapse along the filaments into dense knots. The lowest density regions do not show star formation. These low-density regions are presumably the envelopes and shredded debris of former GMCs. They appear to last a relatively long time; some even get to the next spiral arm (not shown).

# Whirlpool Galaxy ▪ M51

Hubble Heritage

NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-12a


0.15 μm
0.4-0.8 μm
1.2-2.2 μm
3.6 μm
8.0 μm
24 μm
70 μm
160 μm



Molecular Clouds

# Theory of interstellar gas

## (Magneto-)hydrodynamic equations:

1) Navier-Stokes equation (equation of motion):

$$\rho \frac{d\vec{v}}{t} = \vec{k}_{grav} + \vec{k}_{press} + \vec{k}_{frict} + \vec{k}_{mag}; \quad \frac{dv}{dt} = \frac{\partial v}{\partial t} + (\vec{v}\nabla)\vec{v}$$

$$\rho \frac{d\vec{v}}{dt} = -\rho \nabla U - \nabla p + \eta \Delta \vec{v} + \left(\frac{\eta}{3} + \zeta\right) \nabla(\nabla \vec{v}) + \vec{j} \times \vec{B}$$

ρ – mass density
U – gravitational potential
p – pressure
η, ζ – dynamic and volume viscosity

Gas motion driven by 4 forces: gravitation, pressure, friction, magnetic fields.

Assumption:

fluid properties η, ζ, conductivity σ, and ionization X constant

# Theory of interstellar gas

2) Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0$$

Mass conservation of considered medium.

Example: spherical geometry: $$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho v\right) = 0$$

3) Poisson equation

$$\Delta U = -4\pi G \rho$$

G - gravitational constant

The gravitational potential is produced by the local mass density.

# Theory of interstellar gas

4) Thermal equation of state

$$p = p(\rho, T)$$

Trivial example: Ideal gas: $pV = Nk_BT$

$$p = \frac{R}{\mu}\rho T$$

µ – molecular mass, R – Rydberg constant

More general: Polytropic gas: $p \propto \rho^\gamma; \quad \gamma = 1 + \frac{2}{n_f}$

$n_f$ – degrees of freedom: mono-atomic gas: γ = 5/3
di-atomic gas: γ = 7/3
multi-atomic gas: γ = 4/3

Isothermal case (energy radiated away): γ = 1

# Theory of interstellar gas

## Additional equations (often omitted):

5) Caloric equation of state:

$$e = e(\rho, T)$$

- inner energy as function of pressure and temperature

Trivial example: Ideal gas:

$$e = \frac{n_f}{2}\frac{kT}{\mu}$$

6) Heat transfer equation:

$$\rho\frac{\partial e}{\partial t} = -p\nabla\vec{v} + \kappa\Delta T + \frac{\vec{j}^2}{\sigma} + 2\eta v_{ik}v_{ik} - \left(\frac{2}{3}\eta - \zeta\right)(\nabla v)^2 + \Gamma - \Lambda$$

κ – heat diffusion coefficient
Γ – radiative heating
Λ – radiative cooling

7) Magnetohydrodynamics: $\vec{B} = \vec{B}(\rho X_e \vec{v})$

# Heating / Cooling

Heating = Feed of kinetic energy into the gas

- Photoionization of neutral particles
  - Kinetic energy of electrons
- Photoeffect on dust particles
  - Kinetic energy of released electrons
- Cosmic ray ioniziation of neutral particles
  - Kinetic energy of secondary electrons

- X-ray heating
  - Kinetic energy of secondary electrons
- Photodissociation of molecules
  - Kinetic energy of fragments

# Heating / Cooling

Heating:

- UV pumping of $H_2$
  - Radiative excitation of electronic states, collisional de-excitation
- Chemical heating
  - Kinetic energy of reaction products
- Dissipation of turbulence and shocks

- Ambipolar diffusion
  - Differential movement of ions and neutrals in magnetic field
- Gravitational collapse
  - Potential energy

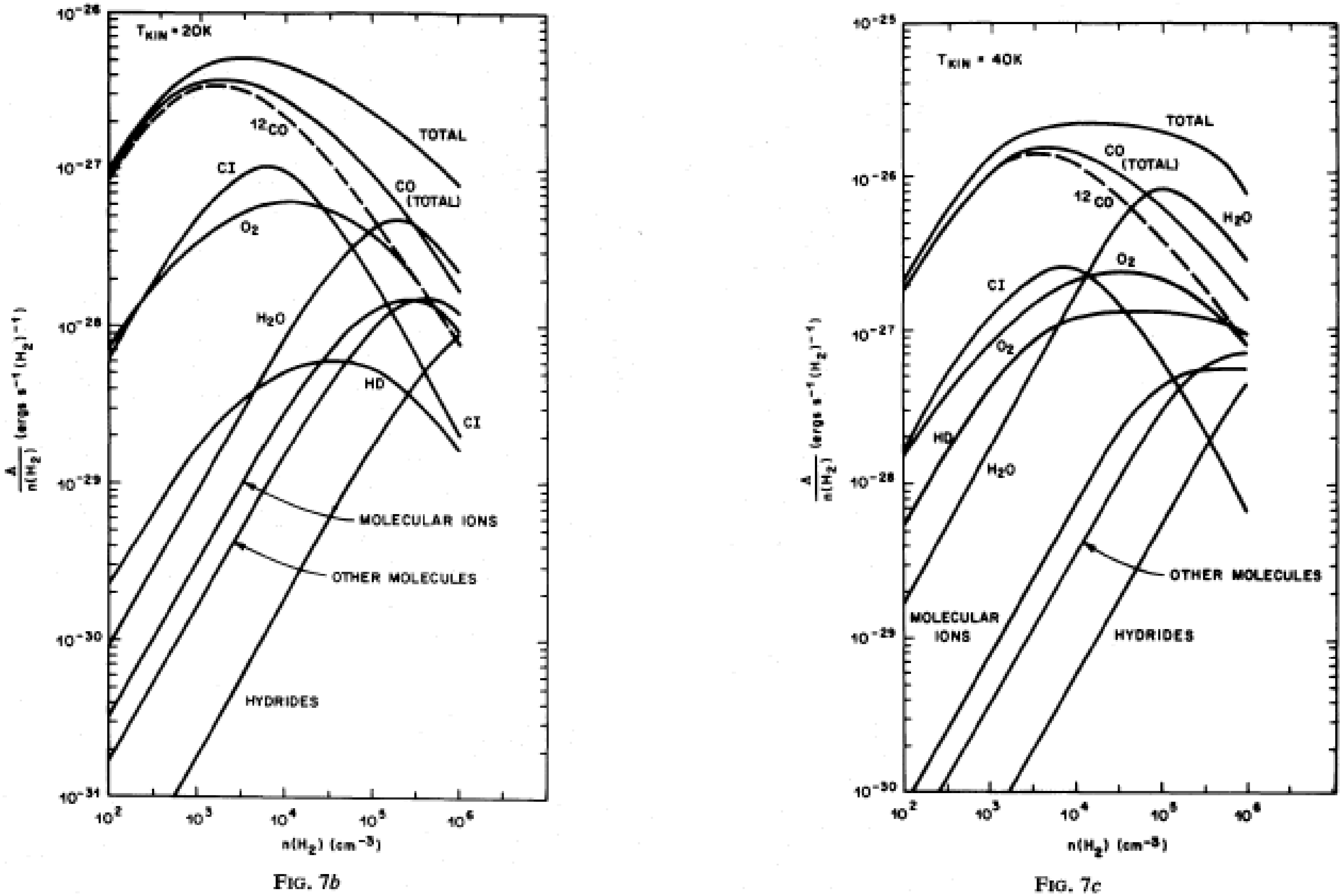
# Heating / Cooling

Cooling:

- Collisional excitation with emission of radiation
  - Molecule, atom or electron with molecule or atom
- Collisions of gas particles with dust
  - Energy lost by dust radiation

- Free-free emission of electrons
  - In HII regions
- Recombination of ionized particles
  - Emission of recombination lines (and continuum)

# Cooling in molecular clouds




FIGS. 7(*a*)–7(*c*).—Total cooling per $H_2$ molecule as a function of $H_2$ density for kinetic temperatures 10 K, 20 K, and 40 K. The fractional abundance for each species has been taken from Table 3.

Goldsmith & Langer 1978

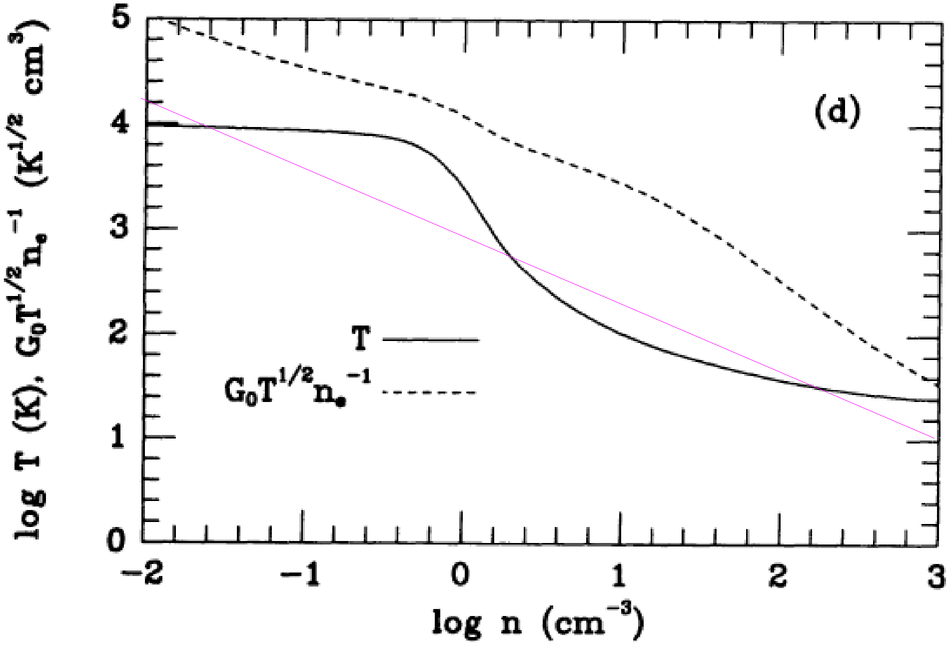
# Thermal instability

Starting point:

- Energy balance equation (assume steady-state): $\partial e / \partial t = \Gamma - \Lambda = 0$
- Pressure equilibrium (p = const.): $T \propto 1/\rho$

Heating processes Γ:

- cosmic rays, radioactive decay
- UV radiation → photo-ionization and dissociation
- Proportional to gas density ρ



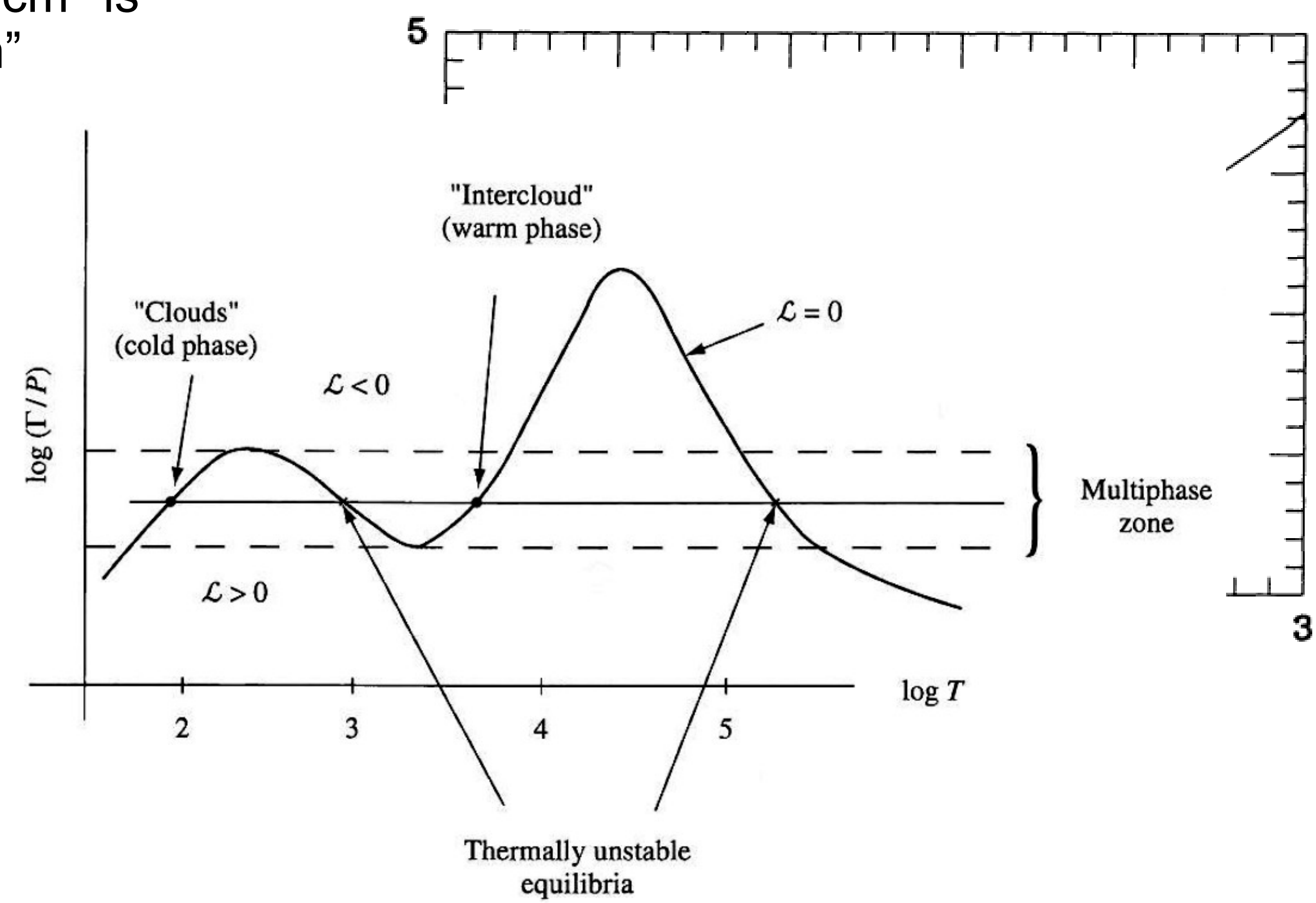

Cooling processes Λ:

- recombination
- Gas-grain cooling
- Collisional excitation of radiation
- Proportional to square of density $\rho^2$
- Threshold processes requiring minimum energy/temperature to work

# Thermal instability

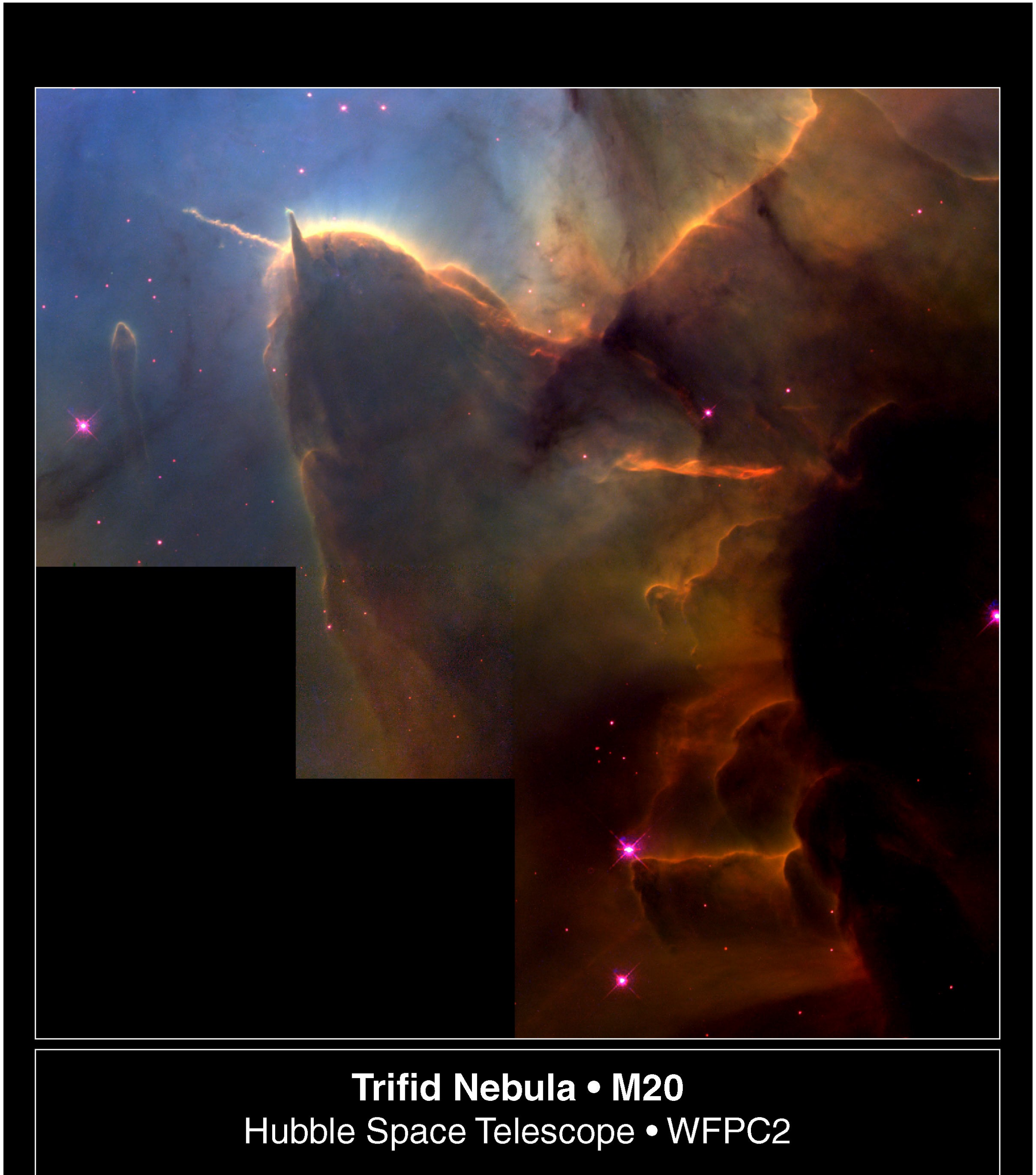
Resulting “equilibrium curve”:

- Two stable branches separated by instable branch
  - The region at densities of about 1cm$^{-3}$ is “forbidden”



# Thermal instability

Produces phase transition
→ sharp cloud boundaries



# The Multiphase Interstellar Medium

- most HI mass seen in 21cm absorption (cold!)
- much of volume filled by HI seen in emission (warm!)

Field (1962): cosmic rays heat intercloud medium to 10,000K, but thermally unstable so clouds form.

Field, Goldsmith, Habing (1969): two phase ISM

warm intercloud phase is stable.

Cox & Smith (1974), McKee & Ostriker (1977)

3$^{rd}$ phase: hot gas from Supernovae and HII Regions

filling factor 0.2 – 0.7 unclear.

# Three-Phase ISM

- 2-Phase + Supernovae produced hot medium

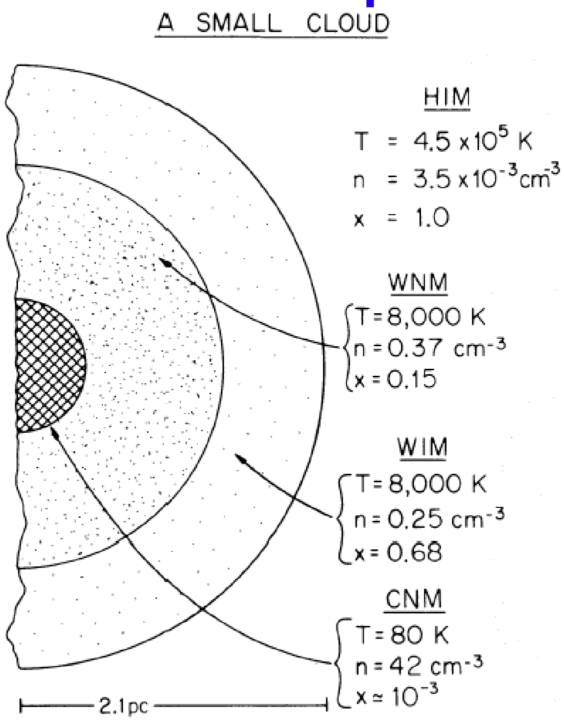



FIG. 1

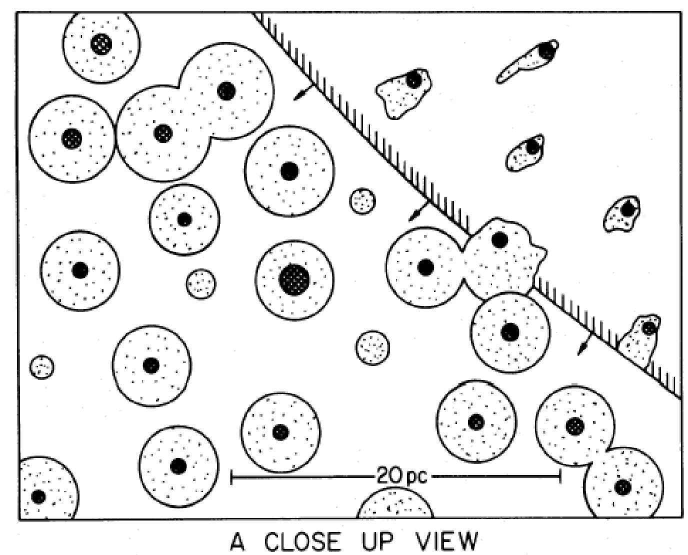



FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density $n$, temperature $T$, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

McKee & Ostriker 1977

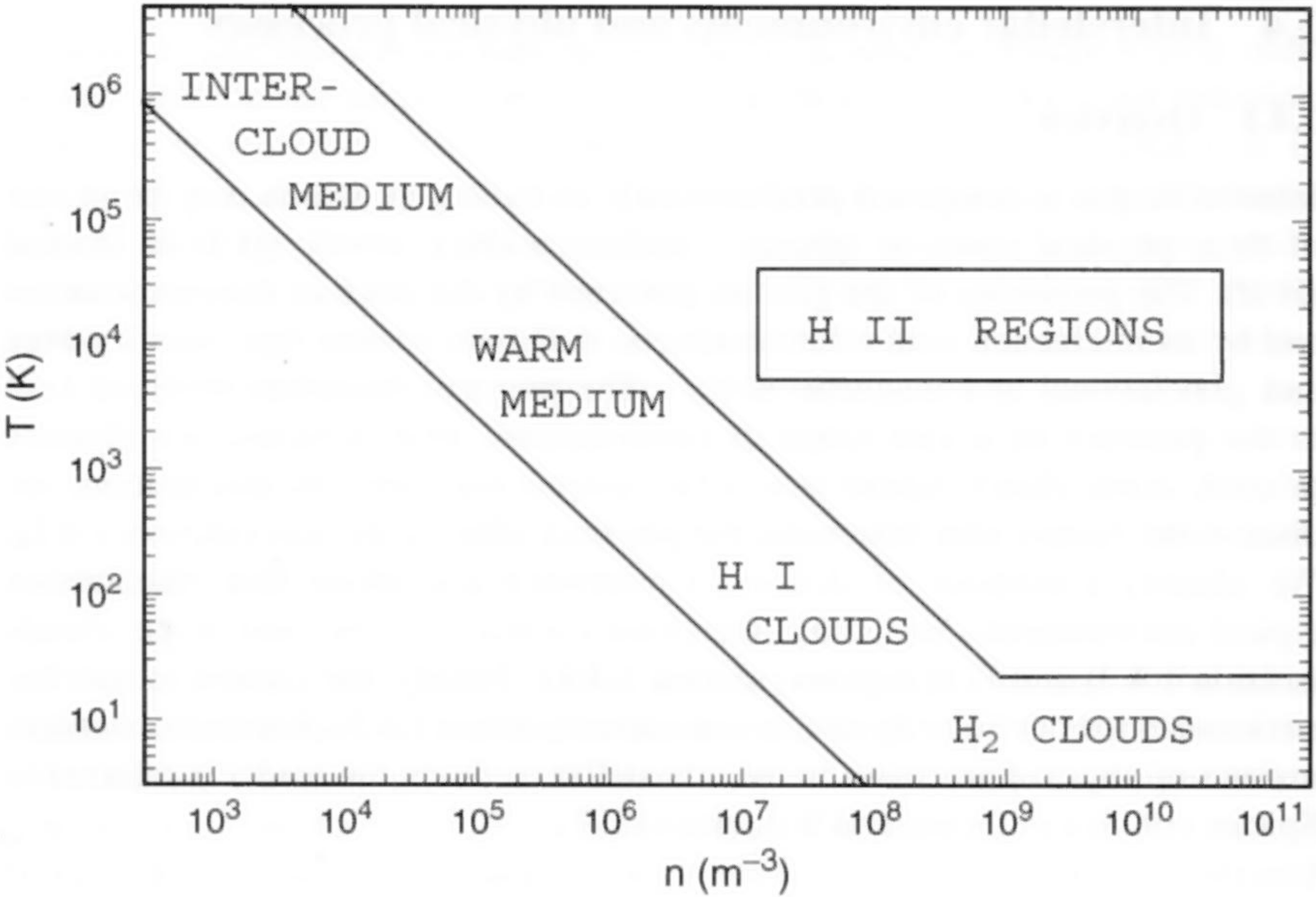
# The phases of the Interstellar Medium (ISM)

Composition of interstellar matter: 90% H, 10% He, traces of other elements
Interstellar hydrogen exists in different chemical forms:

- molecular ($H_2$)
- atomic (HI) : warm and cold phases,
  coexisting in pressure equilibrium ($n.T \sim 3 \times 10^3$ K $cm^{-3}$)
- ionized (HII) : gas illuminated by UV radiation from stars → transient

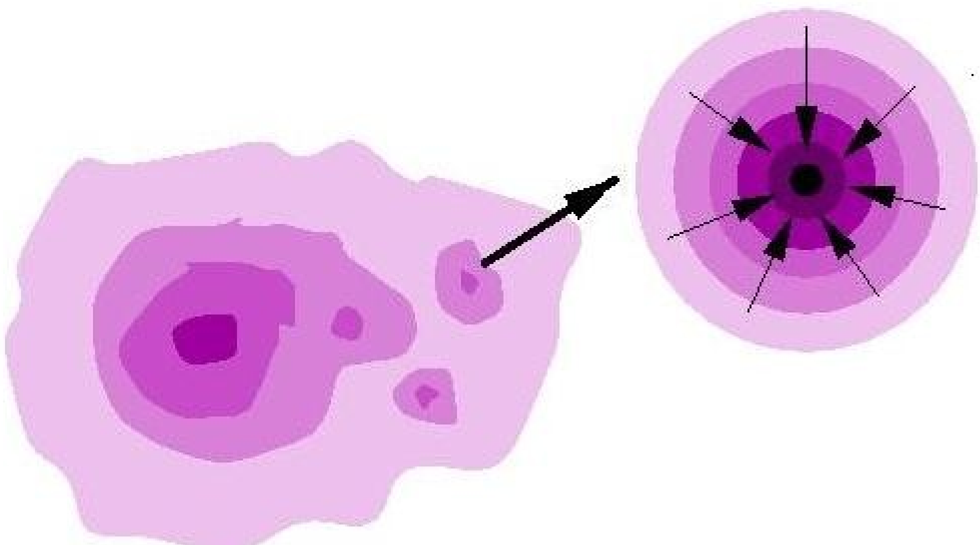
| Phase | Density ($cm^{-3}$) | Temperature (K) | Total mass ($10^9$ $M_{sun}$) |
|---|---|---|---|
| molecular | >300 | 10 | 2.0 |
| cold neutral (HI) | 50 | 80 | 3.0 |
| warm neutral (HI) | 0.5 | 8000 | 4.0 |
| warm ionized | 0.3 | 8000 | 1.0 |
| hot ionized | $3 \times 10^{-3}$ | 500000 | -- |

# Components of the ISM

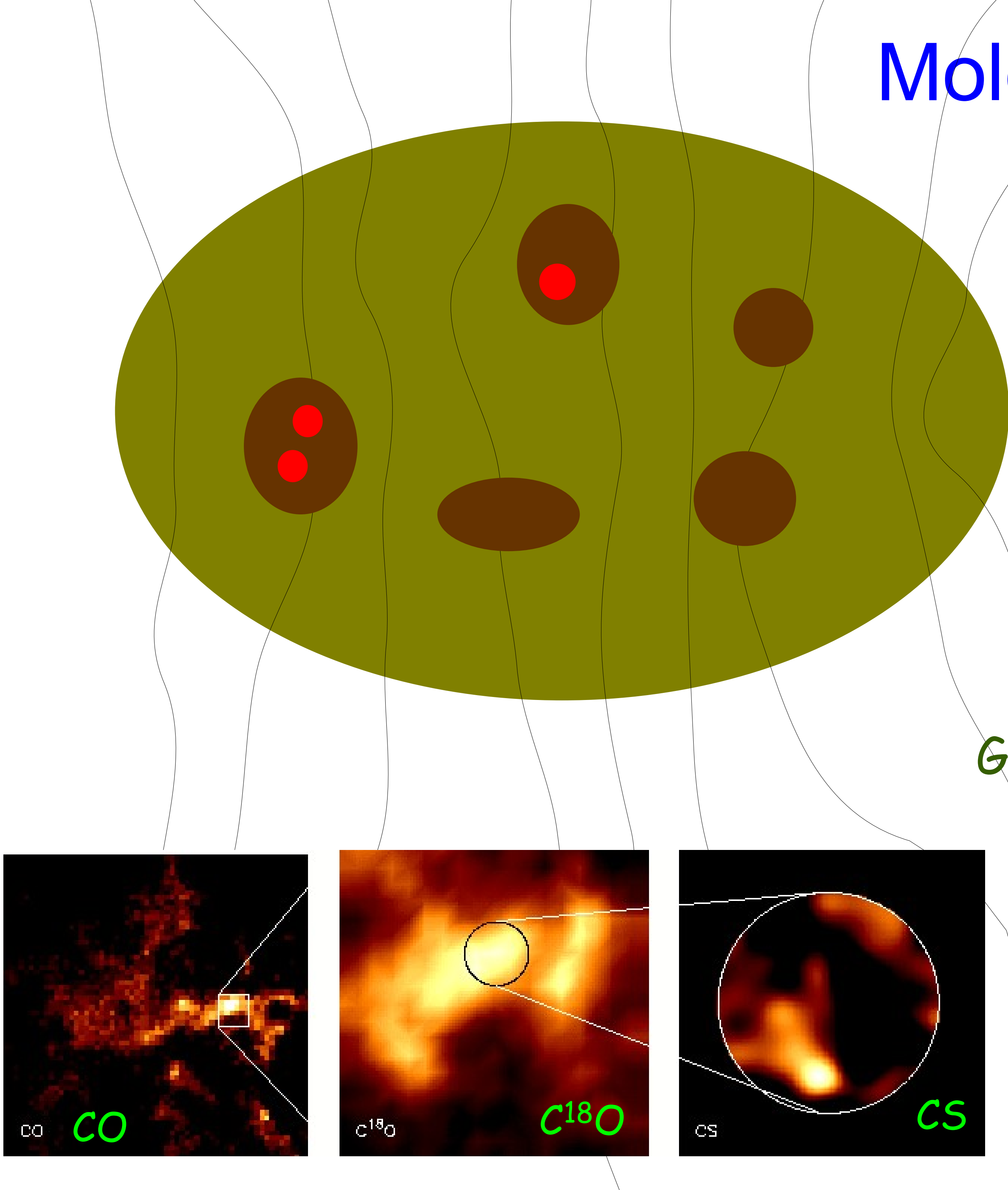


# Molecular clouds

- ...are the places where stars form
- So we have to understand them first



# Molecular Clouds




Diffuse Cloud
(<2mag)

Translucent Cloud
(3-5 mag)

Dark Cloud
(10mag, cold, narrow lines)

Giant Molecular Cloud
4-10mag, warm, broad lines

Clump $f_v$~5%

Core

# Molecular clouds

- dense interstellar matter, forming $H_2$
- visible in CO
- in pressure- and virial equilibrium
- condensations form stars

| Type | Size (pc) | n ($cm^{-3}$) | Temperature (K) | Mass ($M_{sun}$) |
|---|---|---|---|---|
| Giant Molecular Cloud | 50 | $10^2$ | 15 | $10^5$ |
| Dark Cloud Complex | 10 | $5.10^2$ | 10 | $10^4$ |
| Individual Dark Cloud | 2 | $10^3$ | 10 | 30 |
| Dense low-mass Core | 0.1 | $10^4$-$10^5$ | 10 | 10 |

# Dark cloud complexes

- Taurus-Auriga: isolated SF
  - Ungerechts & Thaddeus (1987)
  - 1.2m Columbia telescope, NYC
- ρ Ophiuchus: clus-tered SF

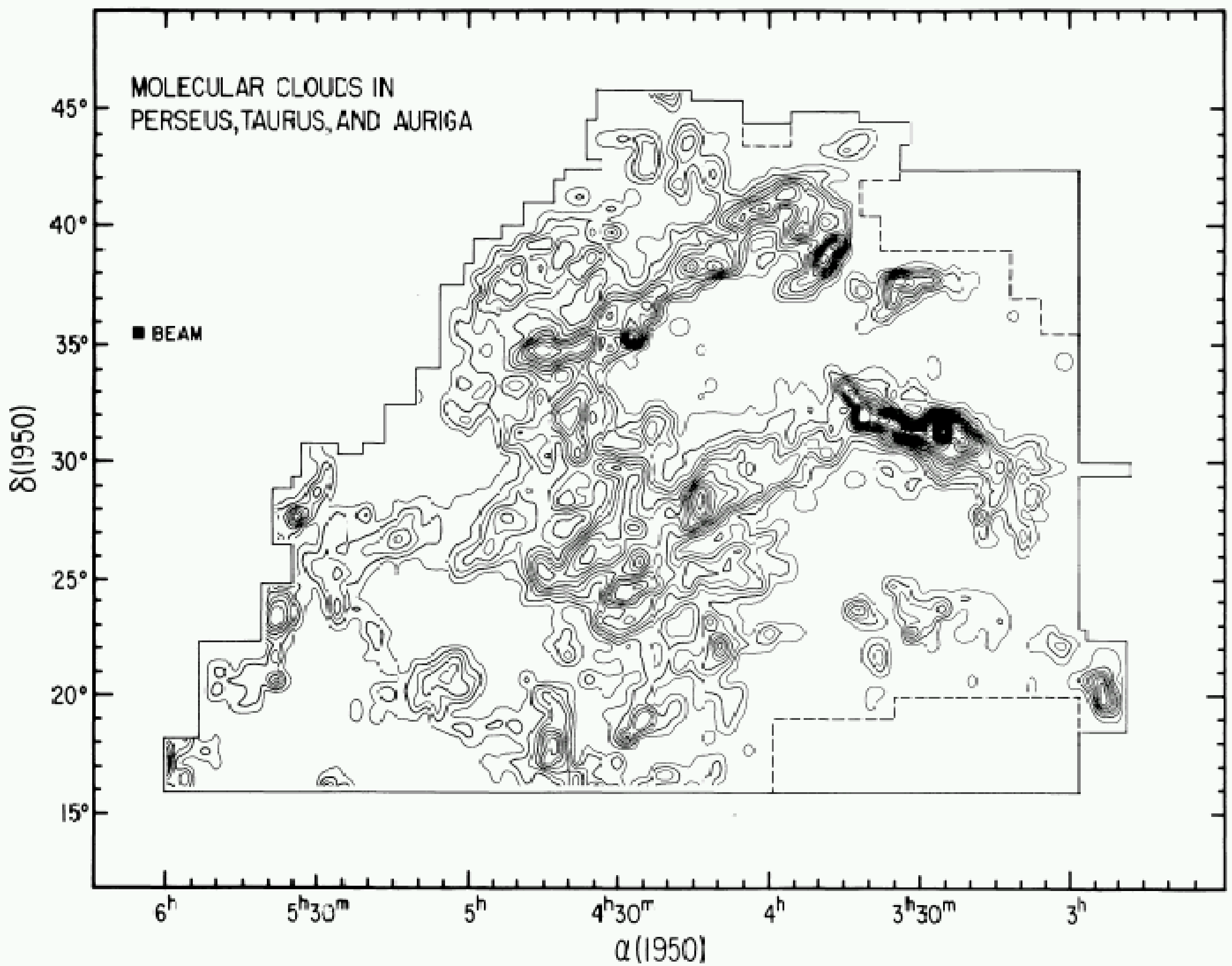
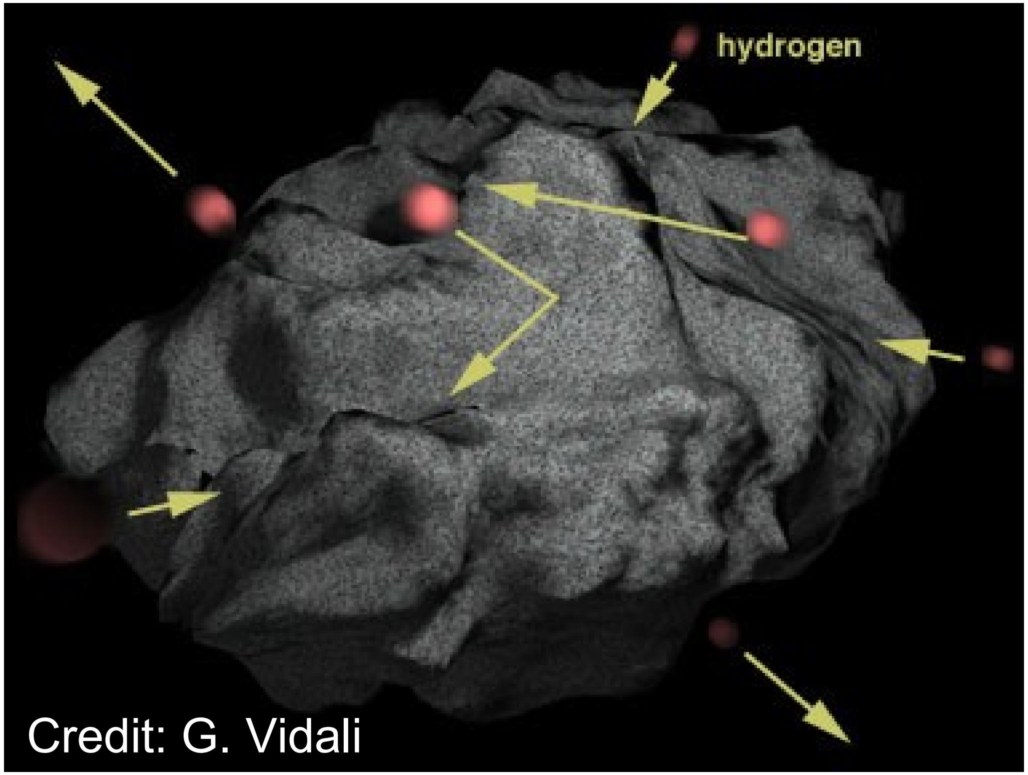


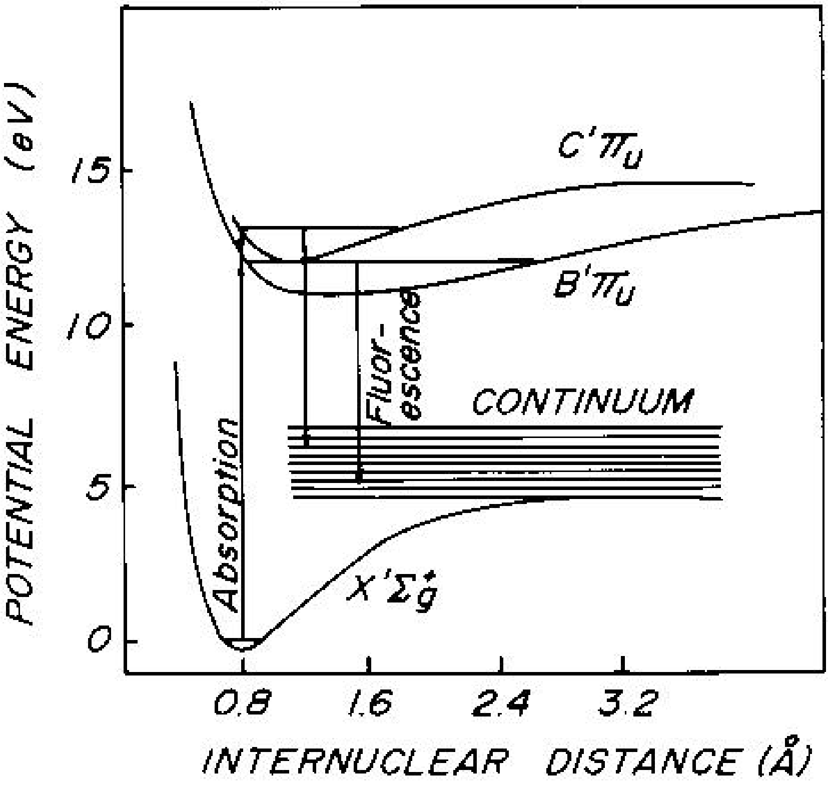

FIG. 1 —Velocity-integrated intensity of CO emission, $W_{CO}$. The lowest contour is 0.5 K km $s^{-1}$, and the separation between contours is 1.5 K km $s^{-1}$. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of $4^m \times 1°$.

# $H_2$ formation and destruction

- Formation on dust grains

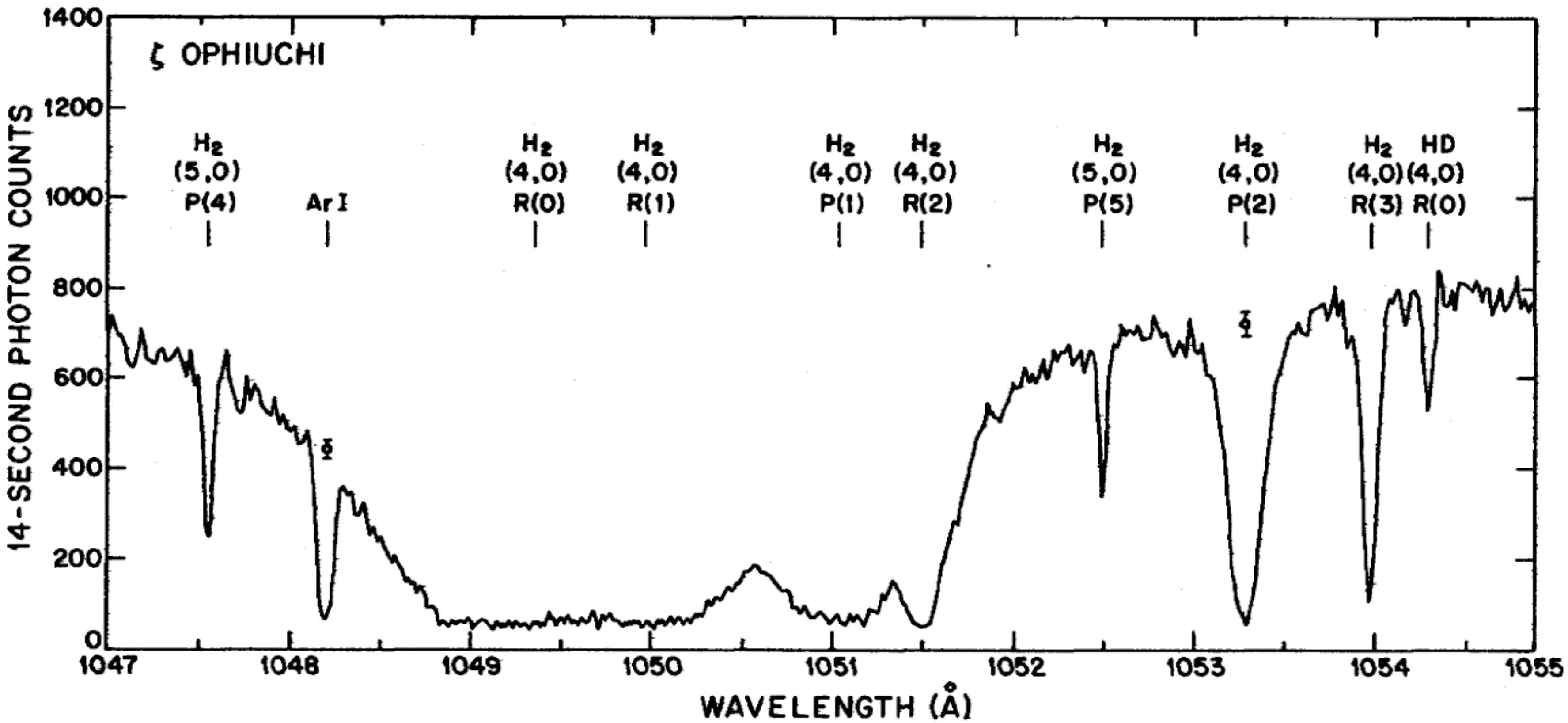



- Destruction by photodisso-ciation



# $H_2$ abundance

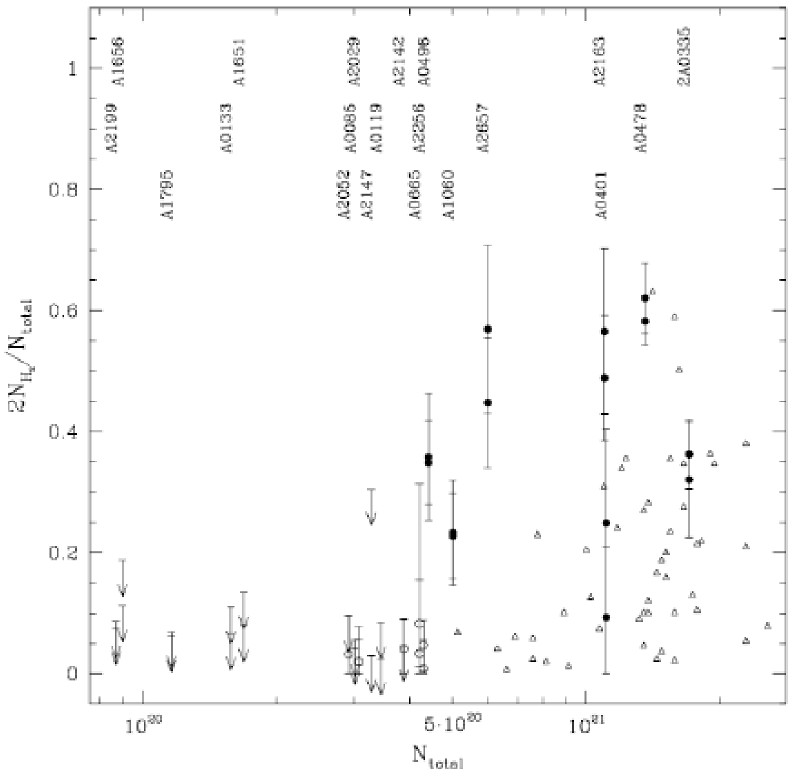
## Interstellar $H_2$ lines towards ζ Ophiuchi



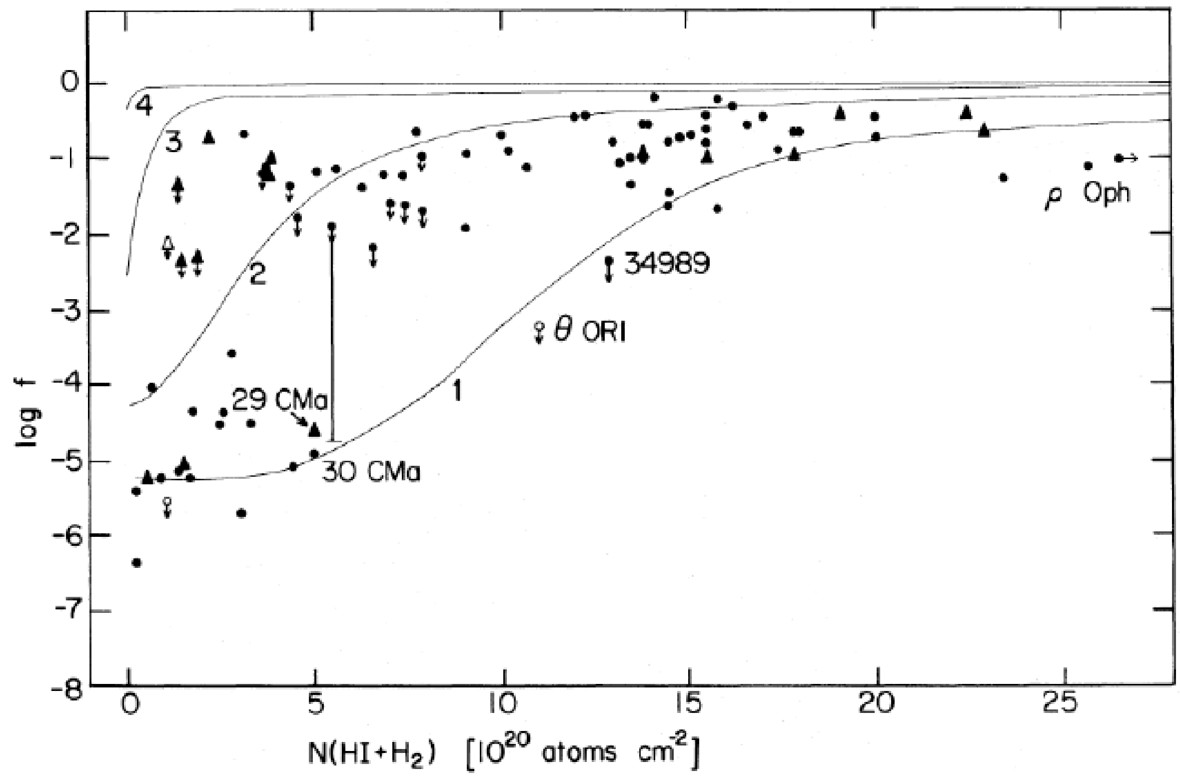

- Copernicus data 1970's
- FUSE data >1999

# $H_2$ abundance

## $H_2$ fraction




Arabadjis & Bregman (1999): X-ray data

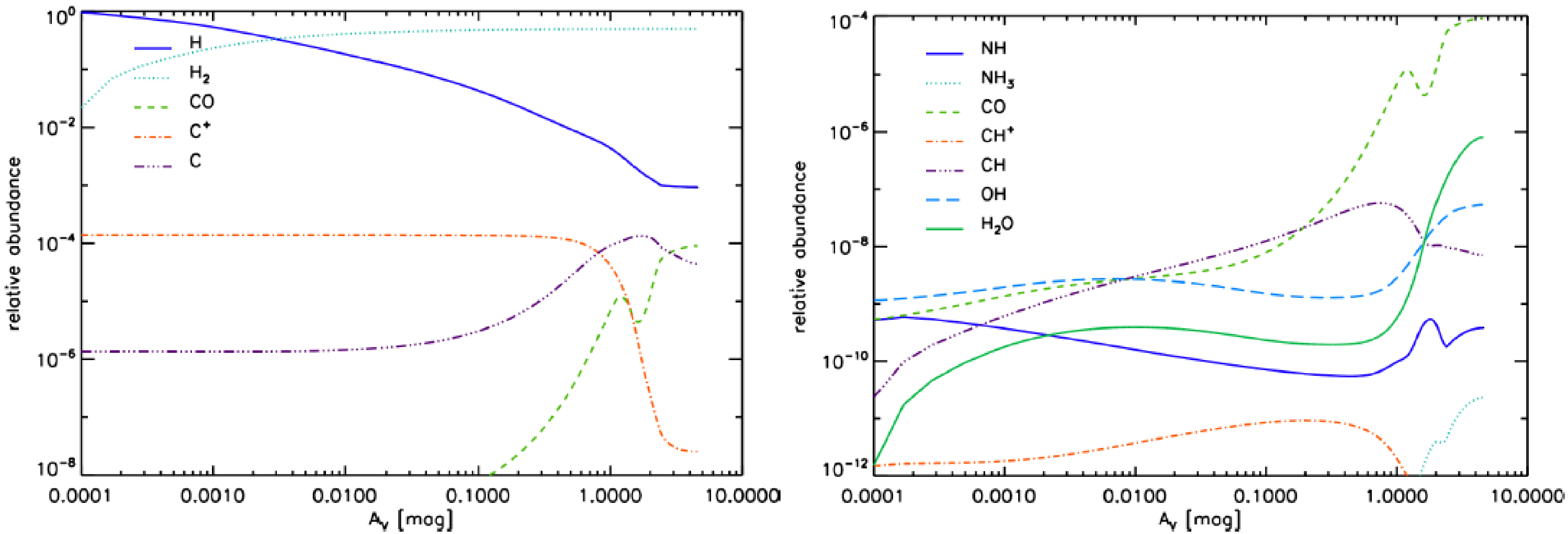



Savage et al. (1977): UV data

- up to 50 % of the CNM+WNM in solar neighbourhood is molecular (Savage 1977)
- $f_{H_2}$ is a steep function of $N(\mathrm{H_{tot}})$, with a critical column density at about $5\,10^{20}$ cm$^{-2}$ (Savage et al. 1977, Liszt & Lucas 2001)

# $H_2$ abundance

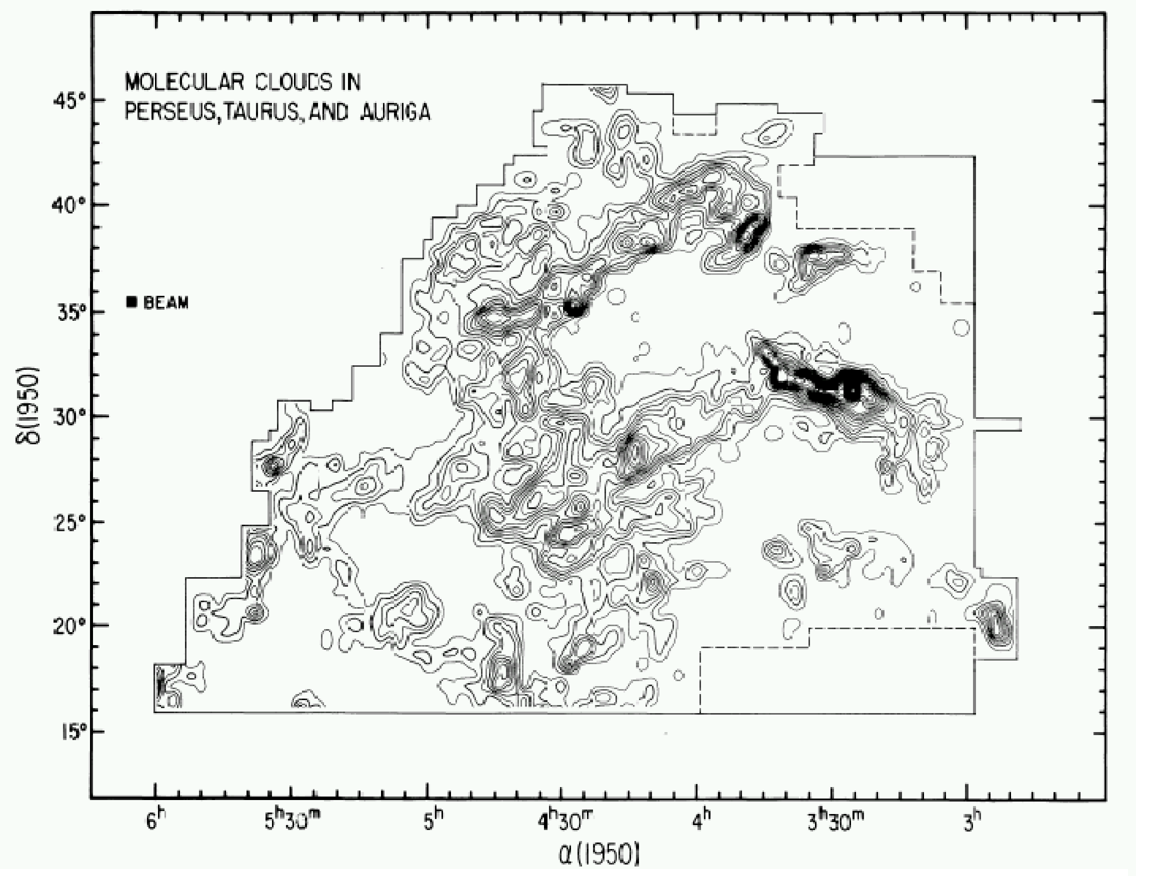
**Density profile and external UV field produce chemical gradients:**




KOSMA-$\tau$ model of a cloud with $\chi = 1, M_{\rm tot} = 100 M_\odot, n = 500$ cm$^{-3}$

- There is no "molecular cloud". Each molecule sees a different size of the cloud.
- None of the mm/sub-mm tracers measures $H_2$. $H_2$ is molecular where many other molecules are dissociated.

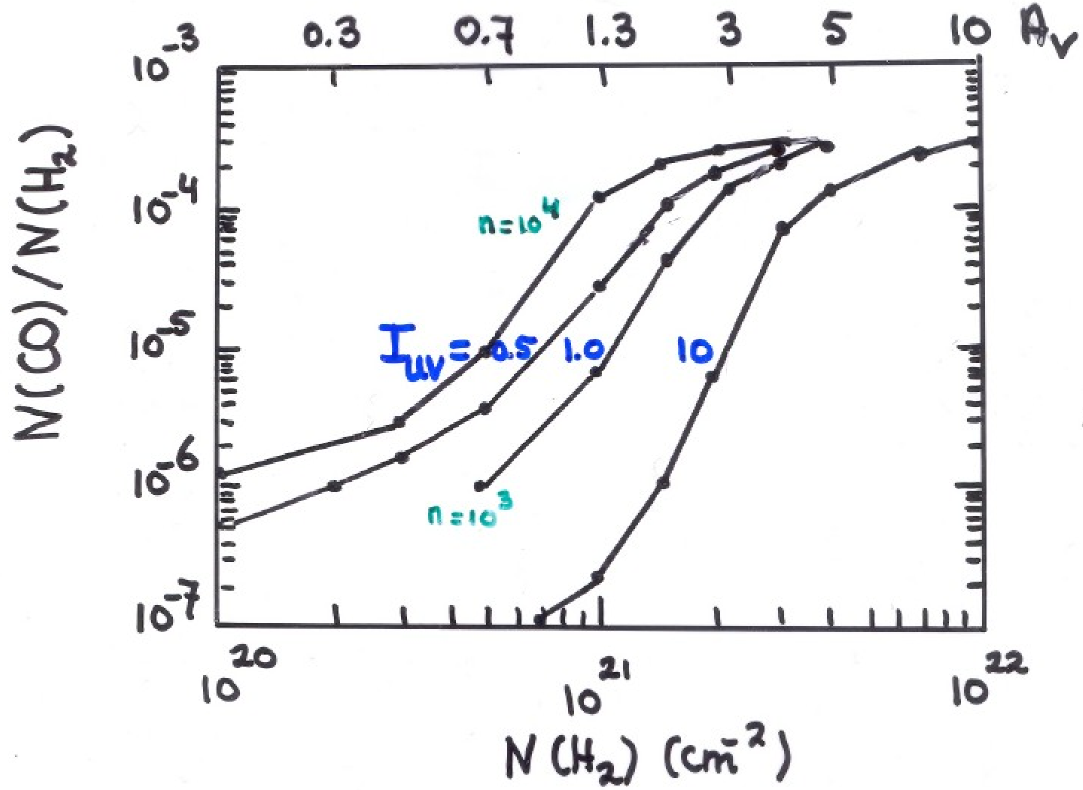
# CO




- CO is most abundant molecule after $H_2$ and is easily observed through (sub-) mm lines $\Rightarrow$
- Good tracer of $H_2$
- CO is very stable ($D_e$ = 11.09 eV $\Leftrightarrow$ 1118 Å) $\Rightarrow$ can only be dissociated at 912 Å < λ < 1118 Å

CO

# Column densities with $A_V$



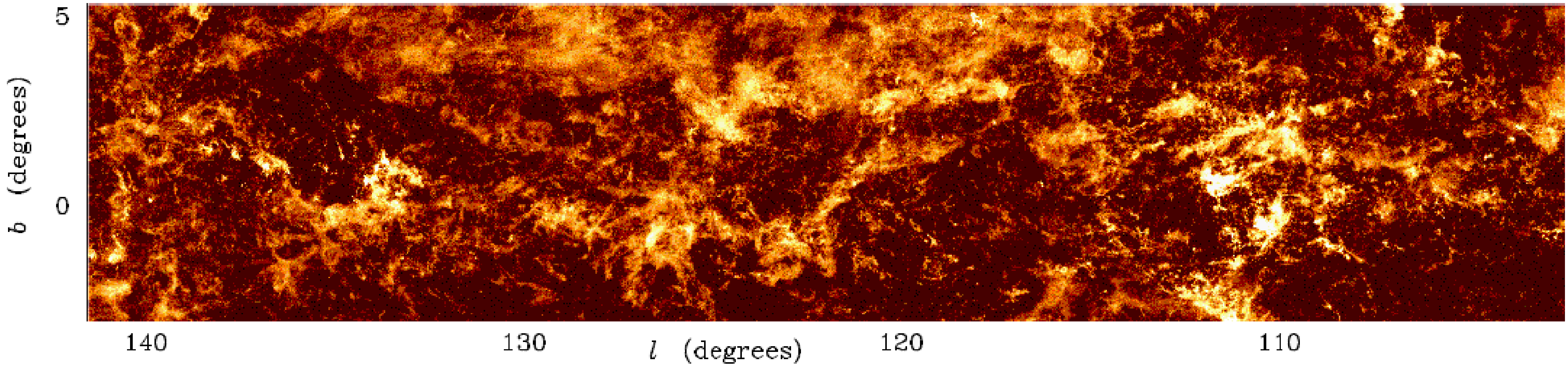

⇒Increase in $CO/H_2$ at $A_V$=1-2 mag from $10^{-7}$ to $10^{-4}$

- Exact location and sharpness transition depend on
  - Strength UV radiation field
  - Density
  - Gas-phase carbon abundance

# CO

## CO fraction

- CO is efficiently formed at $N(\mathrm{H_{tot}}) \gtrsim 2\,10^{21}$ cm$^{-2}$ ($A_V \gtrsim 1$)
- $N(\mathrm{CO}) \propto N(\mathrm{H_2})^2$ (Liszt & Lucas 2001)




Heyer et al. (1998): FCRAO survey of the Outer Galaxy

22 % of the lines of sight through the Outer Galaxy show CO emission above a sensitivity limit of $\approx 2.4$ K for the CO 1–0 line.

# $^{13}CO$ in the inner Galaxy: lots and lots of structure

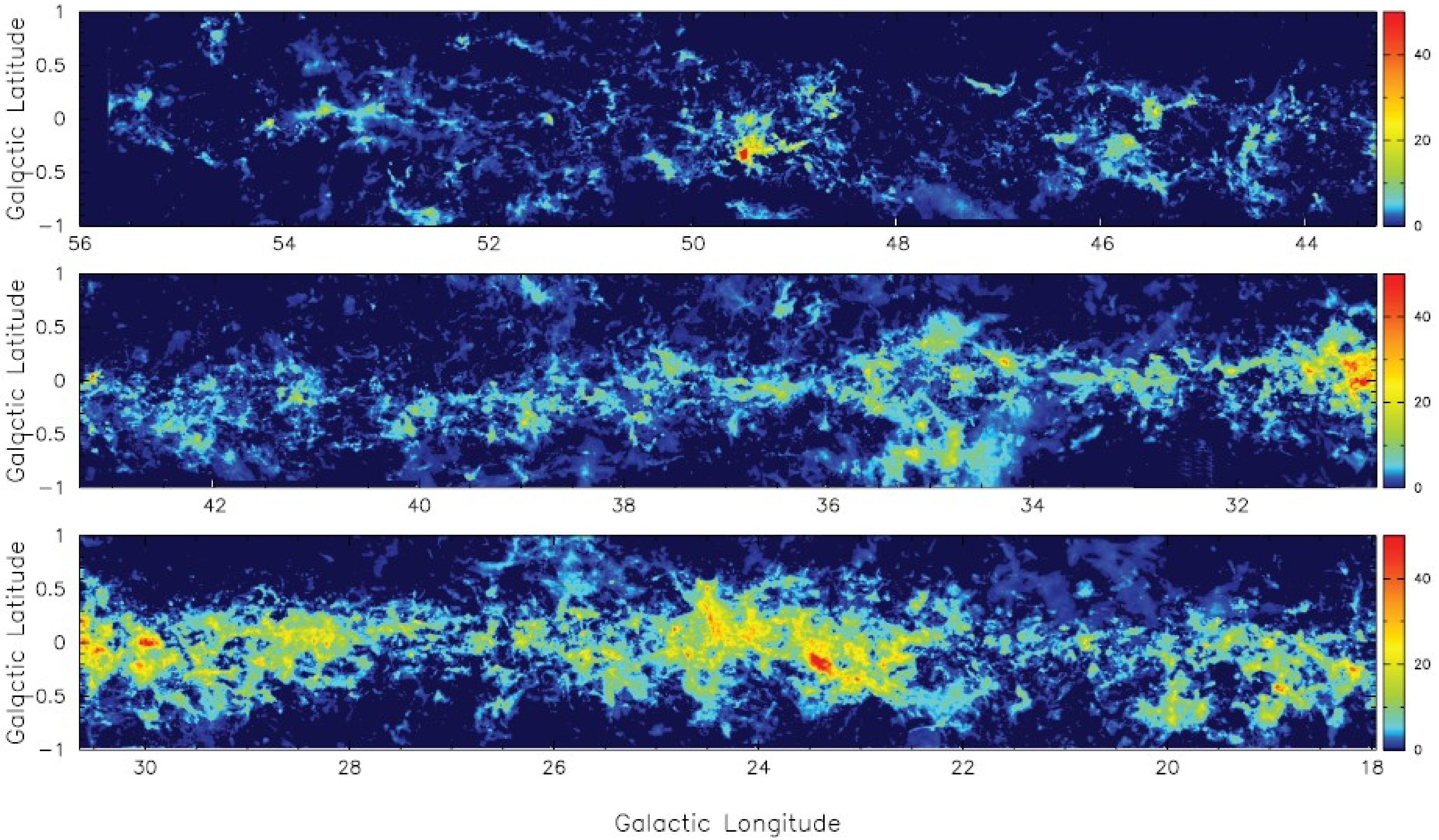



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Fig. 1.—Integrated intensity image (zeroth-moment map) of GRS $^{13}CO$ emission integrated over all velocities ($V_{LSR} = -5$ to 135 km s$^{-1}$ for Galactic longitudes $l \leq 40°$ and $V_{LSR} = -5$ to 85 km s$^{-1}$ for Galactic longitudes $l > 40°$). The image shows that most of the emission is confined to $b \sim 0°$, with concentrations at $l \sim 23°$ and $\sim 31°$. A striking aspect of the image is the abundance of filamentary and linear structures and the complex morphology of individual clouds. The image is in units of K km s$^{-1}$.

Clouds are not smooth, but complex, filamentary, fractal.

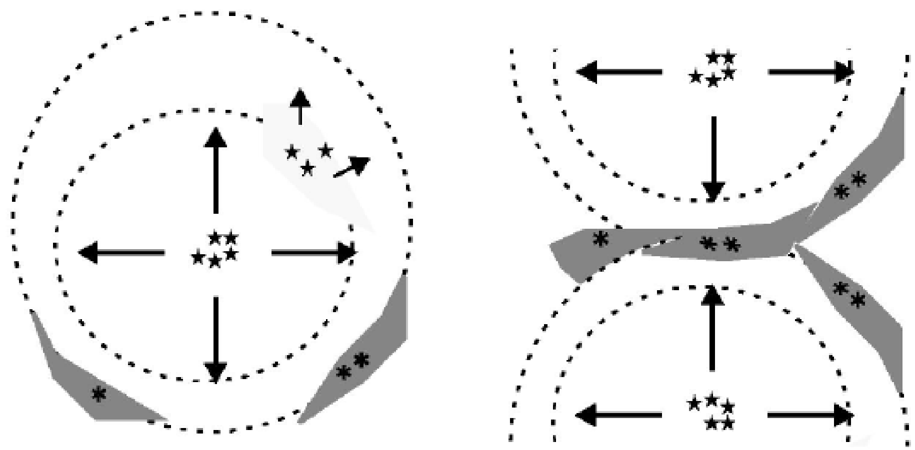
- fractal structures are created by a cascade of interstellar turbulence

# The dynamic picture

- Turbulence in molecular clouds is large-scale driven (Ossenkopf & Mac Low 2002).
- Turbulent clouds are just high-density knots in large scale flows of atomic material (Brunt 2003)
- Clouds are essentially shock-dominated structures (Hartmann et al. 2001)

Implications:

- clouds are short lived (1 . . . 2 Myr)
- turbulent mass transport
- turbulent diffusion
- heating due to turbulence dissipation



Hartmann et al. (2001): triggering of molecular cloud and star formation by large scale flows, rapid dispersal of gas by newly formed stars

Problem:

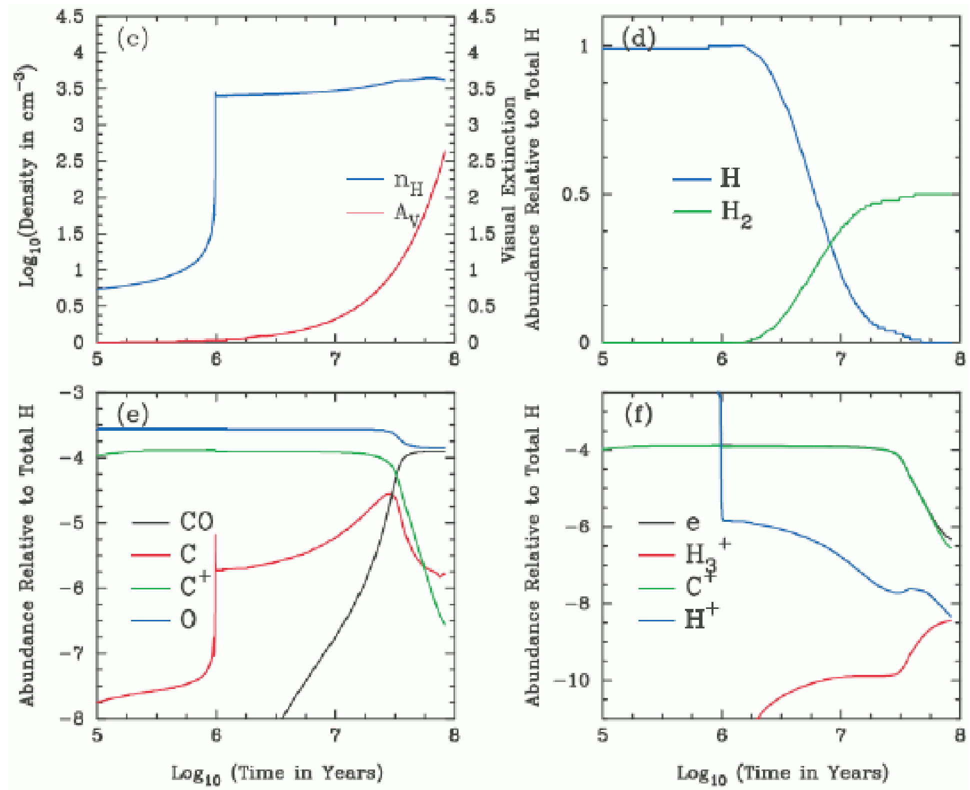
At standard $H_2$ formation rate, $\approx 10^9$yr$/n_H[\text{cm}^{-3}]$, $\tau_{H_2}(300\ \text{cm}^{-3}) = 3$ Myr$> \tau_{\text{cross}}$

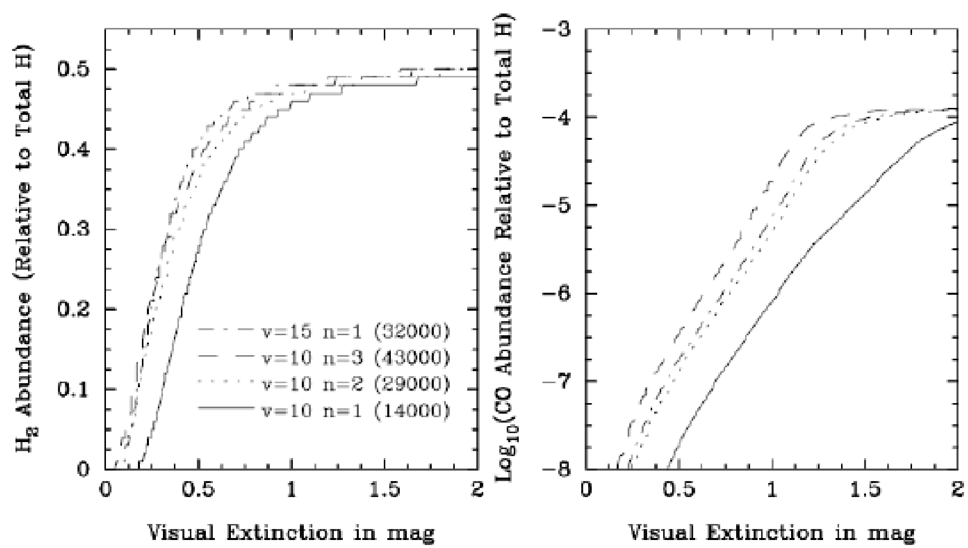
# Fast $H_2$ formation

Solution: $H_2$ formation in short times at high densities created in shocks

Bergin et al. (2004):

- $H_2$ formation in a 1-D slow-velocity (10 km/s) shock in the atomic gas (1 $\mathrm{cm}^{-3}$).
- $H_2$ is efficiently formed and self-shielded.
- CO forms for $A_V > 0.7$ on timescales of 10-20 Myr



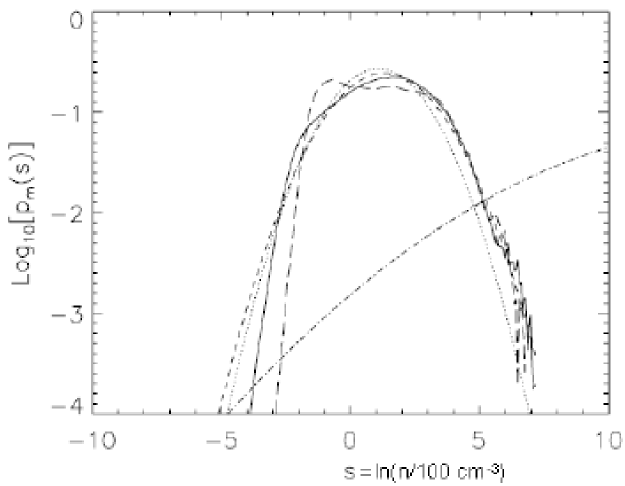



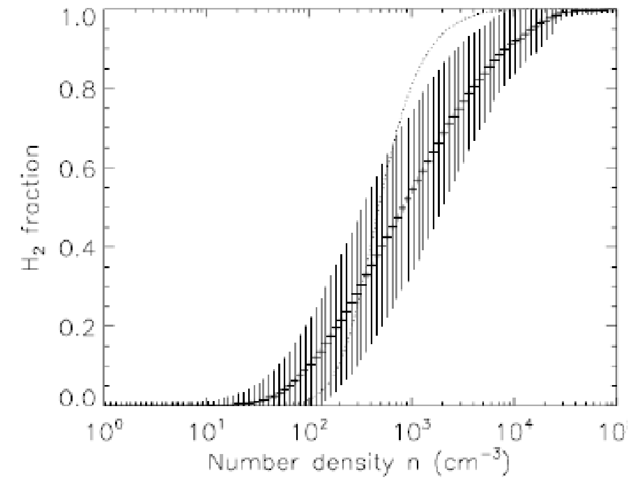
# Fast $H_2$ formation

Distribution of the formed $H_2$ by turbulent advection:

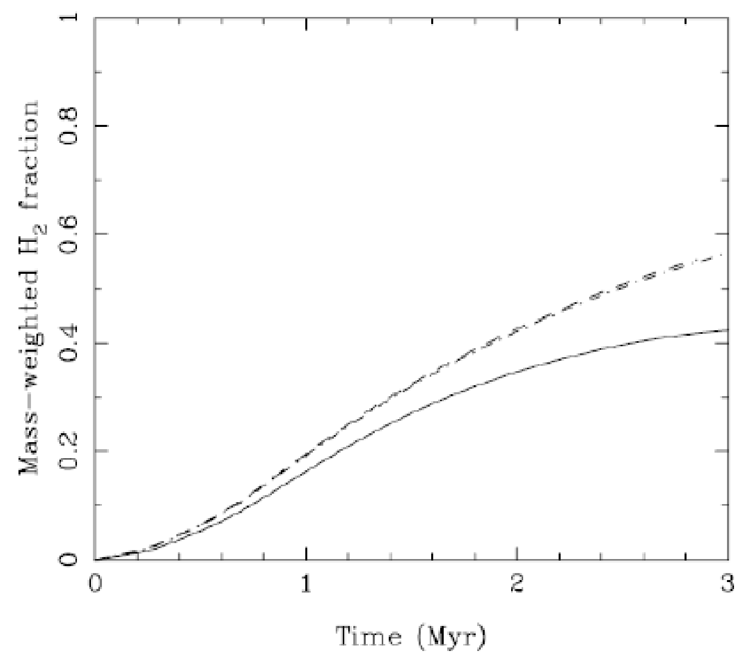
Glover & Mac Low (2007):

Turbulent cloud simulation including $H_2$ formation/self-shielding



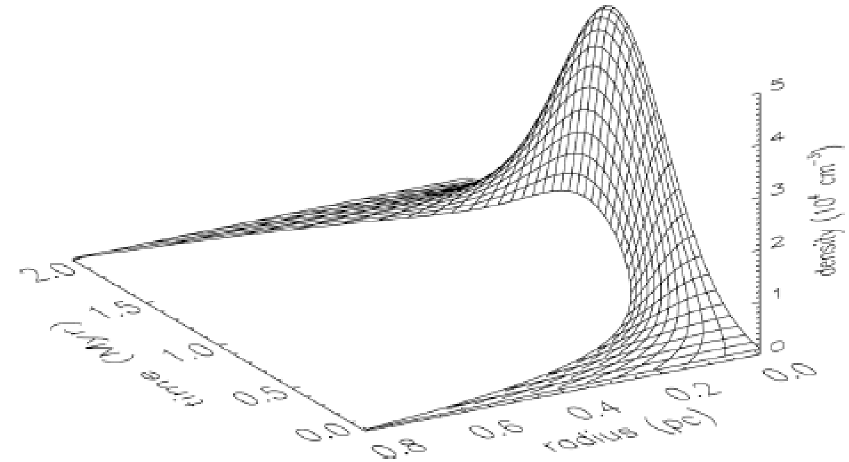




- wide density distribution
- fast $H_2$ formation at $n_{\rm H} \gtrsim 300$ cm$^{-3}$
- turbulent redistribution of $H_2$ gas
- $H_2$ formation rate accelerates by a factor 3-5
- conversion of $\approx 40\%$ of the hydrogen into $H_2$ in the scale of 1-2 Myr

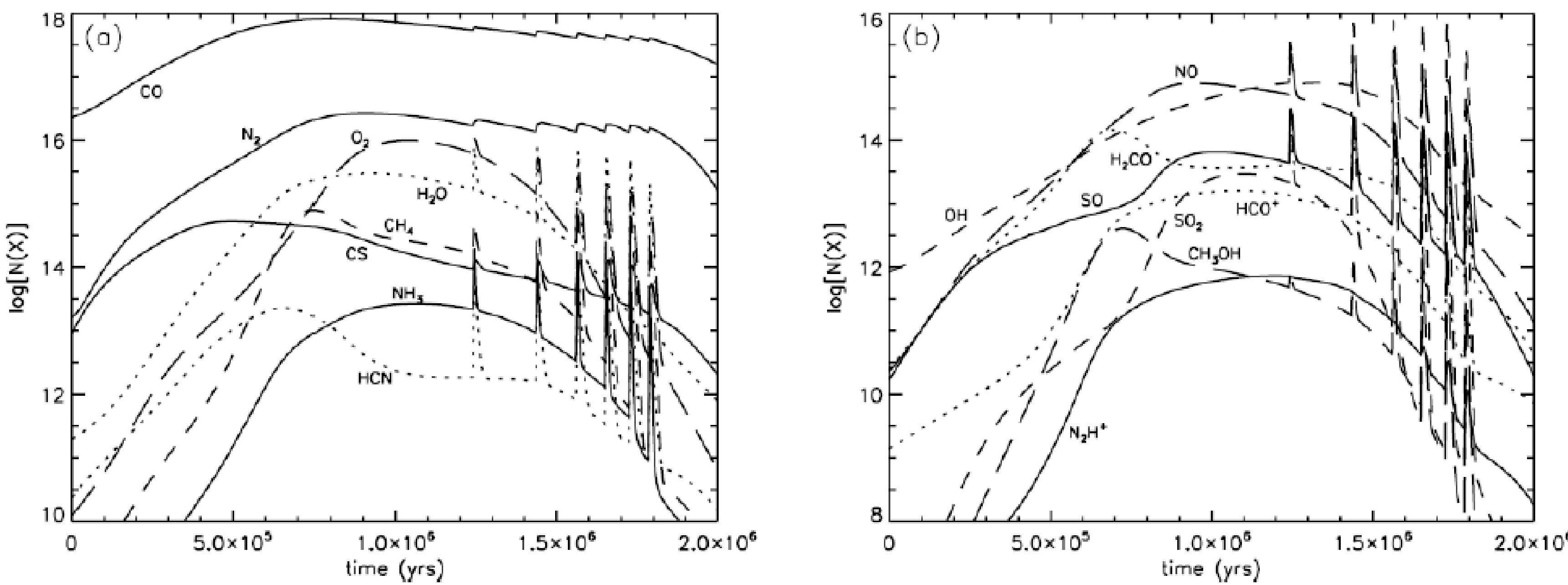


# Fast chemistry

- Model for passage of MHD shock wave
  - compression of cores by factor 50 in 1 Myr
  - initial density 300-1000 $cm^{-3}$
- freeze-out and release of molecules from dust
  - freeze-out threshold $A_V = 2.5$



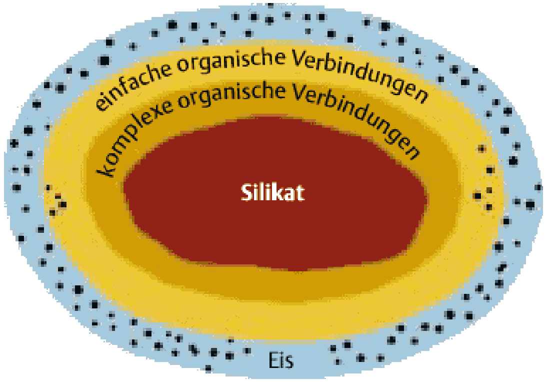

Garrod et al. (2006)




- Very fast formation and destruction of many molecules
- Molecular clouds are ensembles of transient cores

# Dust

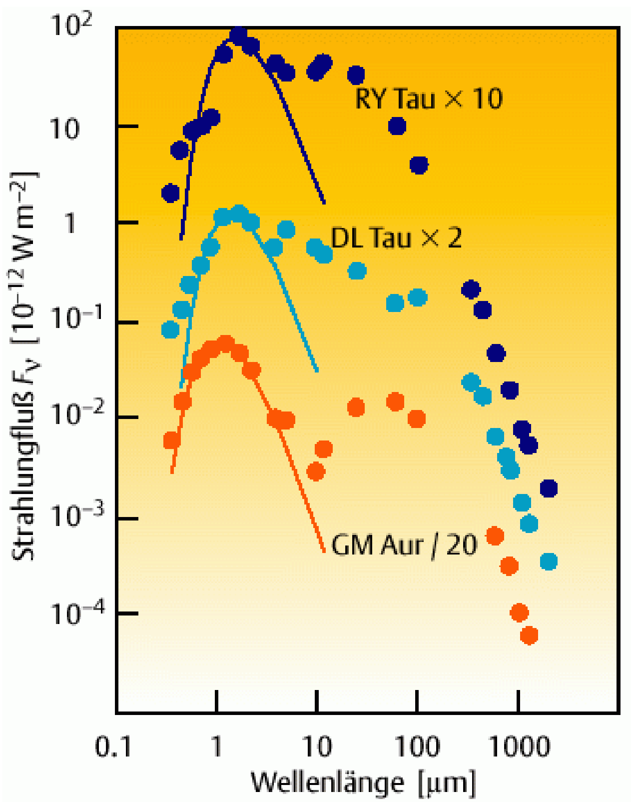
- Essential for cooling
  - Efficient emission through continuous spectrum
- Surface chemistry to form complex molecules
- Diagnostics as optically thin
  (far-) infrared emitter



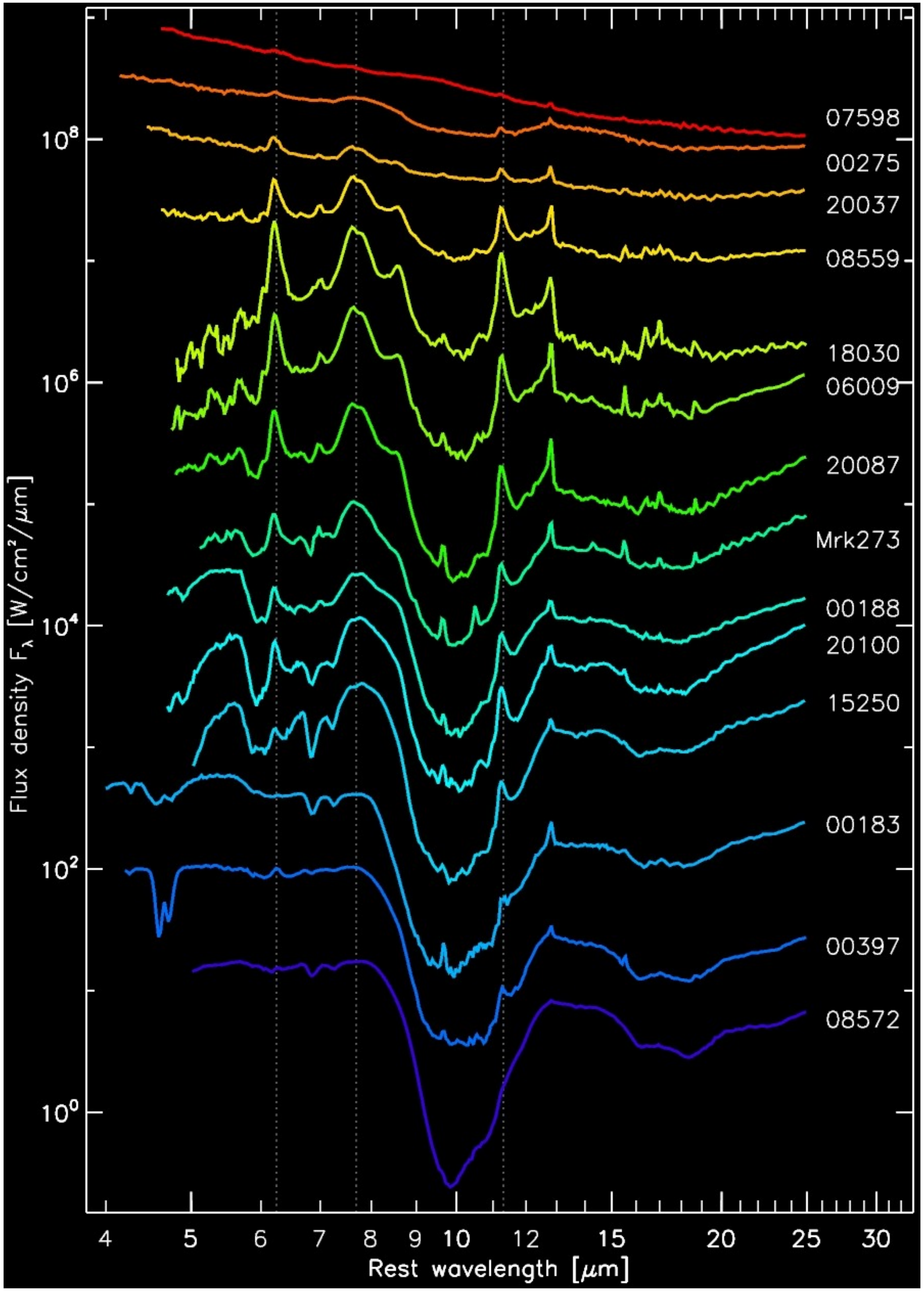

- Silicate and carbonaceous grains
- Organic and icy mantles
- Size spectrum from few Å to µm
  → typical size 0.1µm
- Irregular structure

# Dust

- Re-emits 99% of the total energy injected into the ISM

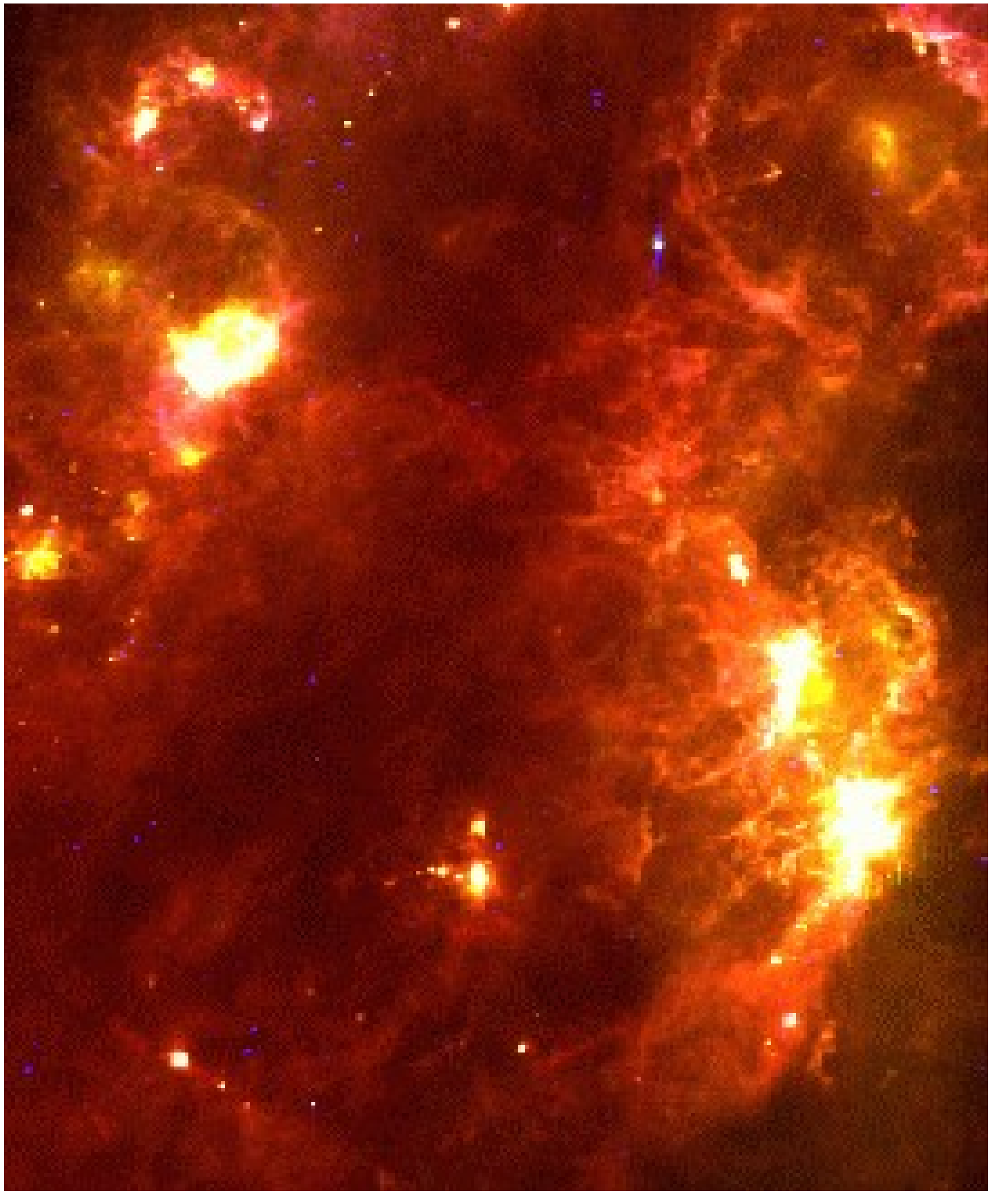



- Spectroscopy traces composition

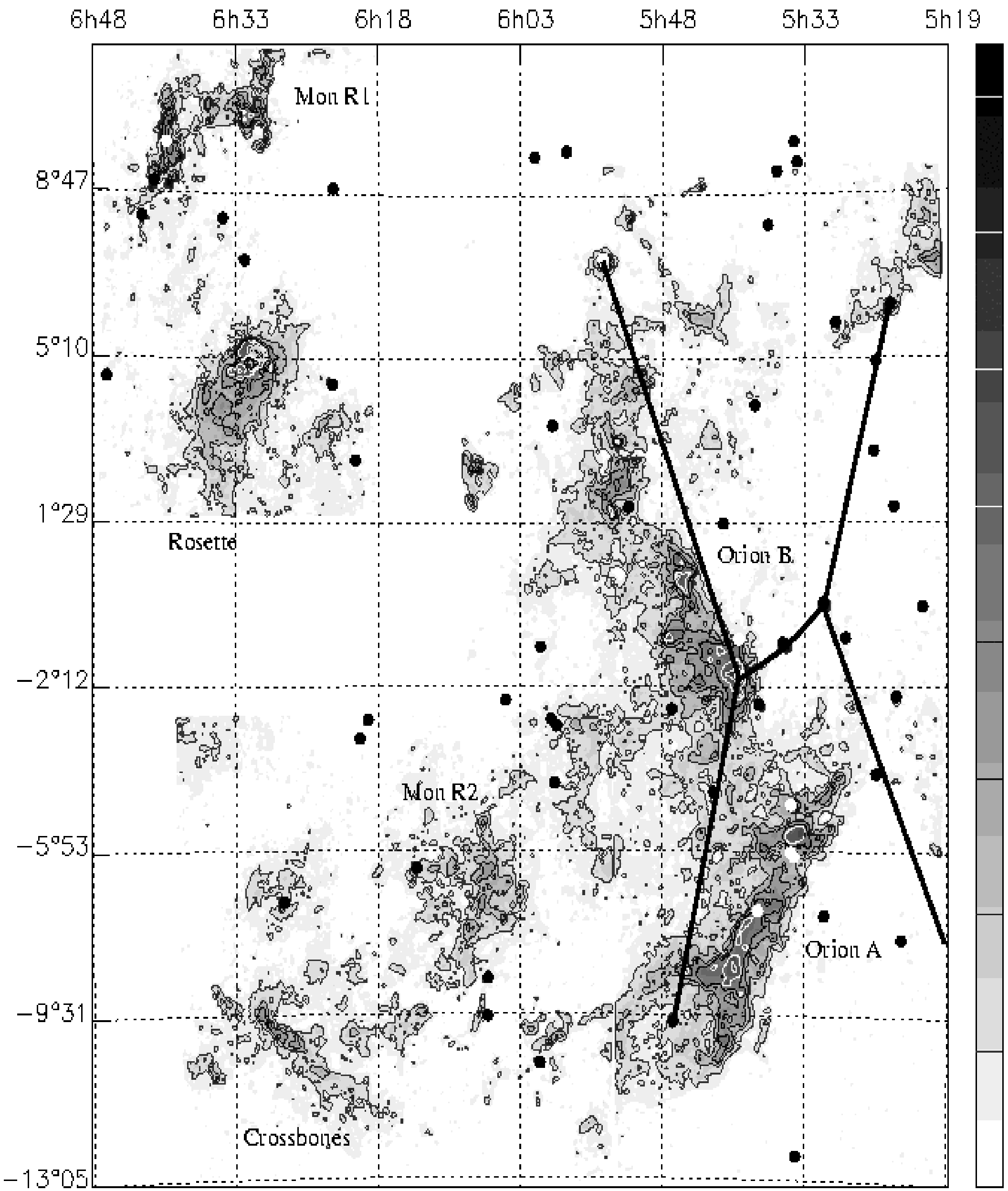



Infrared spectra of ultra-luminous galaxies (Lahuis et al)

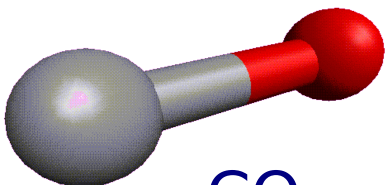
# IRAS 100 μm



# Starcounts

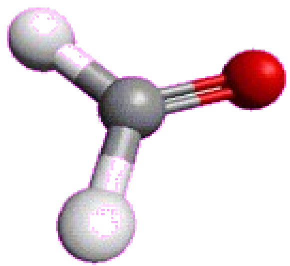


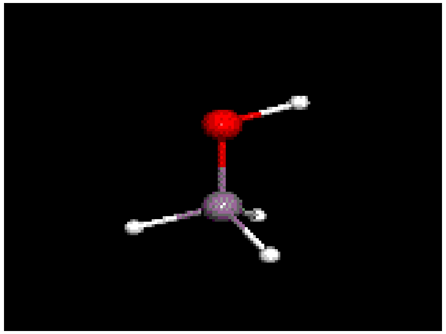
# Interstellar Chemistry



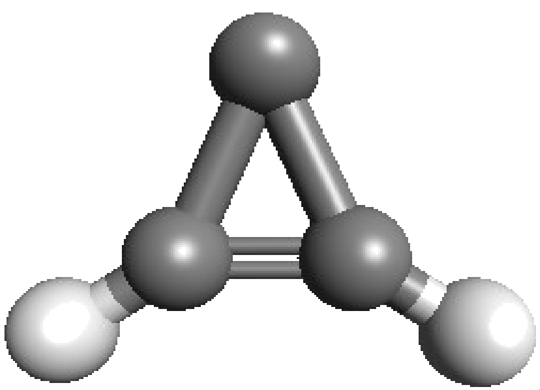
CO

Formaldehyde ($H_2CO$)



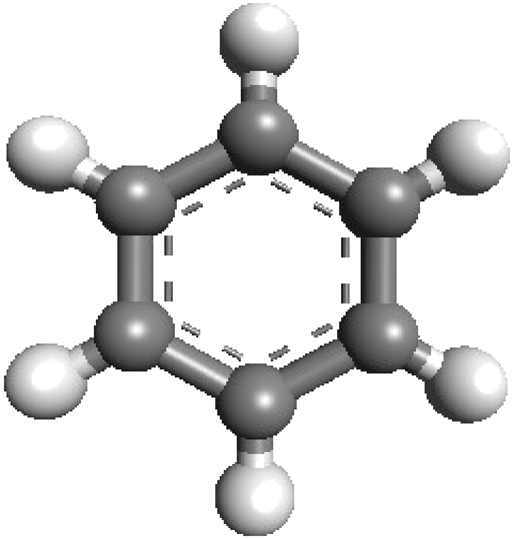


Methanol $CH_3OH$



$C_3H_2$

Benzene ($C_6H_6$)

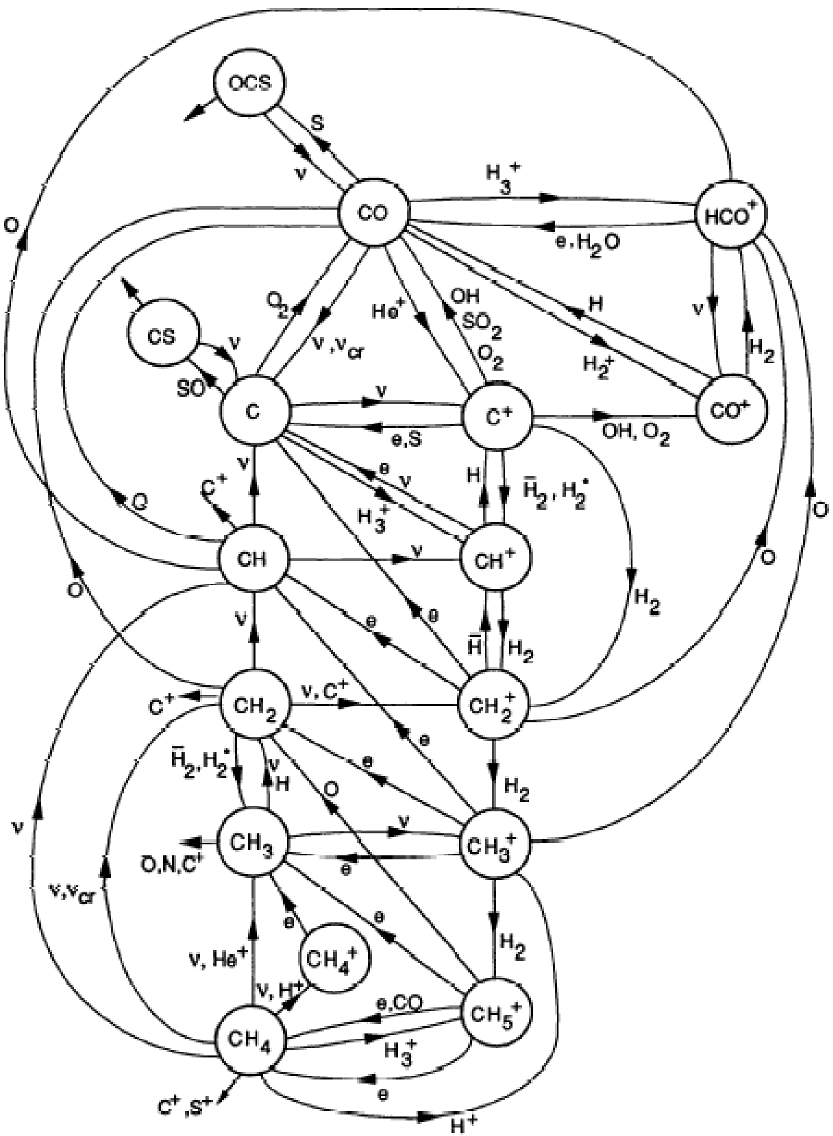


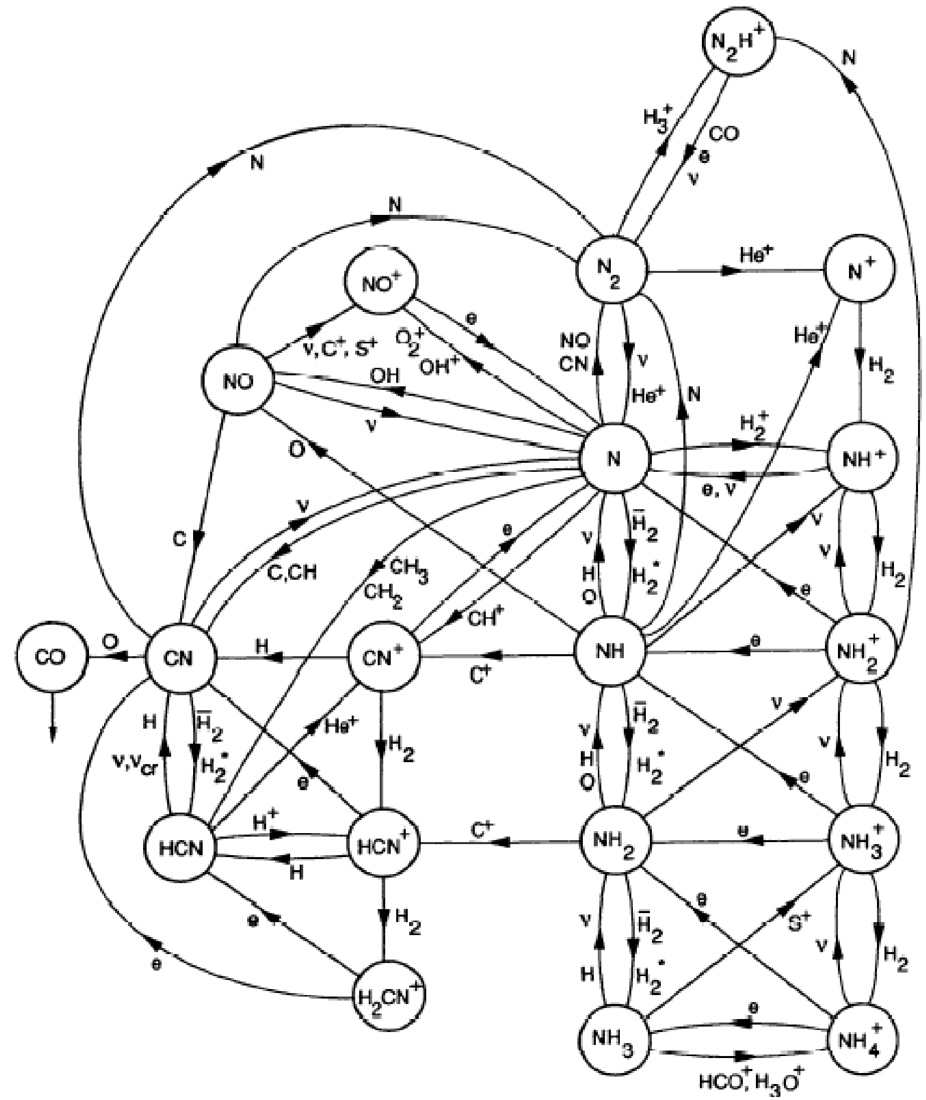
# Interstellar Chemistry

## Networks of chemical reactions

- Formation of bonds
  - Radiative association: $X^+ + Y \rightarrow XY^+ + h\nu$
  - Grain surface: $X + Y{:}g \rightarrow XY + g$
- Destruction of bonds
  - Photo-dissociation: $XY + h\nu \rightarrow X + Y$
  - Dissociative recombination: $XY^+ + e \rightarrow X + Y$
- Rearrangement of bonds
  - Ion-molecule reactions (fast): $X^+ + YZ \rightarrow XY^+ + Z$
  - Neutral-neutral reactions (slow): $X + YZ \rightarrow XY + Z$

# Interstellar Chemistry




Chemical networks of reactions

Carbon

Nitrogen

# Interstellar Chemistry

## Quantification of reaction rates

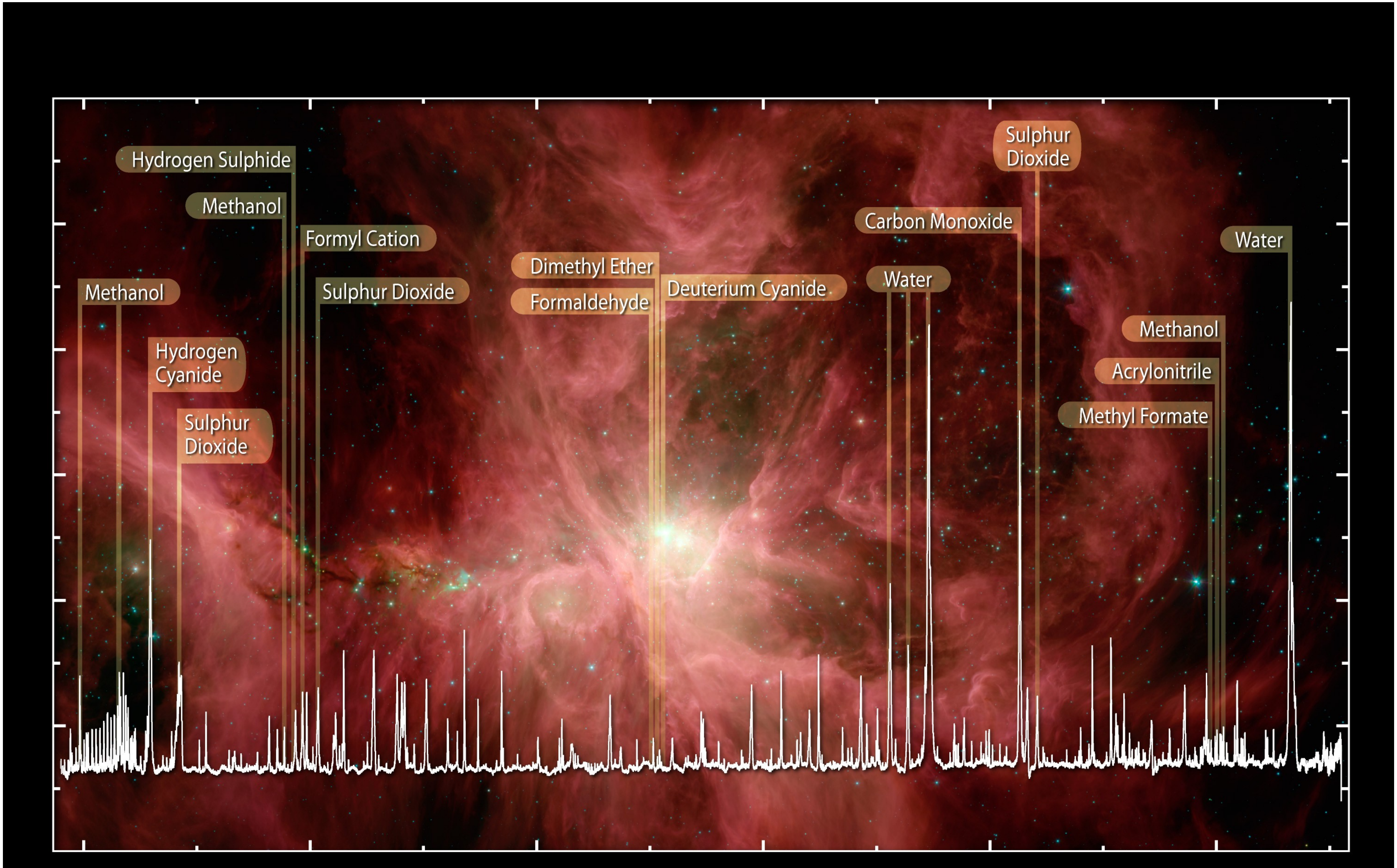
- Depend on temperature, UV field and cosmic ray rate

| Reactants | | Products | | $k_{ij}$ ($cm^{+3}$ $s^{-1}$) | $E_a$ (K) |
|---|---|---|---|---|---|
| H | HNO | NO | H2 | 3.68E+05 | 1.50E+03 |
| H | HCS | H2CS | | 1.94E+12 | 0.00E+00 |
| H | OCN | HNCO | | 1.94E+12 | 0.00E+00 |
| H | OCS | CO | HS | 1.94E+12 | 0.00E+00 |
| H | C2O | HC2O | | 1.94E+12 | 0.00E+00 |
| H | C3O | HC3O | | 1.94E+12 | 0.00E+00 |
| H | HC2O | CH2CO | | 1.94E+12 | 0.00E+00 |
| H | HC3O | H2C3O | | 1.94E+12 | 0.00E+00 |
| H | H2O2 | O2H | H2 | 5.16E+04 | 1.90E+03 |
| H | CH4 | CH3 | H2 | 1.27E-01 | 5.94E+03 |
| H | C2H6 | C2H5 | H2 | 1.44E+00 | 4.89E+03 |
| H | CHNH | CH2NH | | 1.94E+12 | 0.00E+00 |
| H | CH2N | CH2NH | | 1.94E+12 | 0.00E+00 |
| H | CH3N | CH3NH | | 1.94E+12 | 0.00E+00 |
| H | CHNH2 | CH2NH2 | | 1.94E+12 | 0.00E+00 |
| H | CH3NH | CH3NH2 | | 1.94E+12 | 0.00E+00 |
| H | CH2NH2 | CH3NH2 | | 1.94E+12 | 0.00E+00 |
| H | H3C3N | H4C3N | | 3.19E+07 | 7.50E+02 |
| H | H4C3N | H5C3N | | 1.94E+12 | 0.00E+00 |
| H2 | CN | HCN | H | 1.33E+00 | 2.07E+03 |
| H2 | NH2 | NH3 | H | 2.49E-08 | 6.30E+03 |
| H2 | CH2 | CH3 | H | 1.58E-03 | 3.53E+03 |
| H2 | CH3 | CH4 | H | 1.82E-08 | 6.44E+03 |

| Species | $k_{crd}$ ($s^{-1}$) | $E_D$ (K) |
|---|---|---|
| H | 6.00E-09 | 3.50E+02 |
| H2 | 1.20E-09 | 4.50E+02 |
| HE | 5.70E-08 | 1.00E+02 |
| C | 4.20E-12 | 8.00E+02 |
| N | 3.90E-12 | 8.00E+02 |
| O | 3.70E-12 | 8.00E+02 |
| NA | 6.70E-80 | 1.18E+04 |
| MG | 9.30E-40 | 5.30E+03 |
| SI | 8.30E-24 | 2.70E+03 |
| S | 4.20E-14 | 1.10E+03 |
| FE | 3.60E-33 | 4.20E+03 |
| CH | 3.00E-11 | 6.54E+02 |
| NH | 5.40E-11 | 6.04E+02 |
| OH | 6.30E-15 | 1.26E+03 |
| C2 | 1.10E-14 | 1.21E+03 |
| NAH | 3.80E-81 | 1.20E+04 |
| MGH | 2.60E-41 | 5.55E+03 |
| FEH | 1.00E-34 | 4.45E+03 |
| CN | 1.60E-16 | 1.51E+03 |
| N2 | 9.80E-15 | 1.21E+03 |
| CO | 9.80E-15 | 1.21E+03 |
| SIH | 2.80E-25 | 2.94E+03 |
| NO | 9.40E-15 | 1.21E+03 |

# Interstellar Chemistry

## Systematic line searches

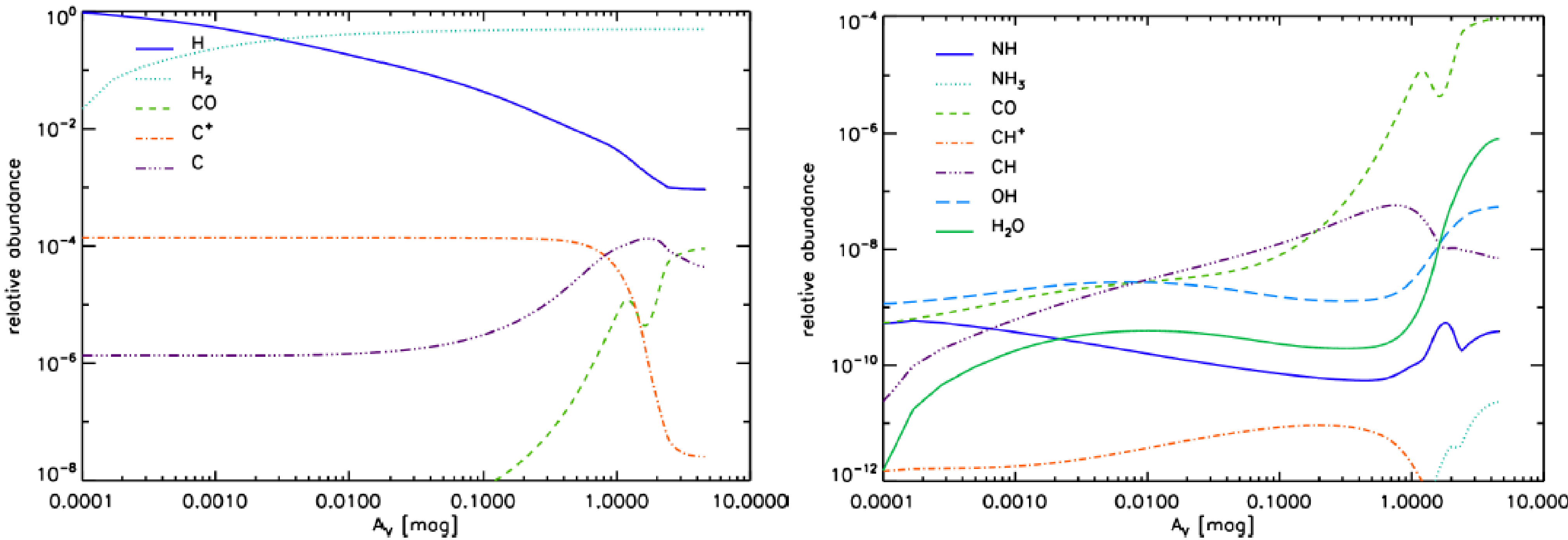


# Molecules in space

| 2 Atome | 3 Atome | 4 Atome | 5 Atome | 6 Atome | 7 Atome | 8 Atome | 9 Atome | 10 Atome | 11 Atome | 12 Atome | 13 Atome |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ | $C_3$ | c-$C_3H$ | $C_5$ | $C_5H$ | $C_6H$ | $CH_3C_3N$ | $CH_3C_4H$ | $CH_3C_5N$ | $HC_9N$ | $C_6H_6$ | $HC_{11}N$ |
| AlF | $C_2H$ | l-$C_3H$ | $C_4H$ | l-$H_2C_4$ | $CH_2CHCN$ | $HCOOCH_3$ | $CH_3CH_2CN$ | $(CH_3)_2CO$ | $CH_3C_6H$ | $C_2H_5OCH_3$ | |
| AlCl | $C_2O$ | $C_3N$ | $C_4Si$ | $C_2H_4$ | $CH_3C_2H$ | $CH_3COOH$ | $(CH_3)_2O$ | $(CH_2OH)_2$ (?) | $C_2H_5OCHO$ | $C_3H_7CN$ | |
| $C_2$ | $C_2S$ | $C_3O$ | l-$C_3H_2$ | $CH_3CN$ | $HC_5N$ | $C_7H$ | $CH_3CH_2OH$ | $H_2NCH_2COOH$ (?) | | | |
| CH | $CH_2$ | $C_3S$ | c-$C_3H_2$ | $CH_3NC$ | $CH_3CHO$ | $H_2C_6$ | $HC_7N$ | $CH_3CH_2CHO$ | | | |
| $CH^+$ | HCN | $C_2H_2$ | $CH_2CN$ | $CH_3OH$ | $CH_3NH_2$ | $CH_2OHCHO$ | $C_8H$ | | | | |
| CN | HCO | $NH_3$ | $CH_4$ | $CH_3SH$ | c-$C_2H_4O$ | l-$HC_6H$ (?) | $CH_3CONH_2$ | | | | |
| CO | $HCO^+$ | HCCN | $HC_3N$ | $HC_3NH^+$ | $H_2CCHOH$ | $CH_2CHCHO$ (?) | $C_8H^-$ | | | | |
| $CO^+$ | $HCS^+$ | $HNCH^+$ | $HC_2NC$ | $HC_2CHO$ | $C_6H^-$ | $CH_2CCHCN$ | $CH_2CHCH_3$ | | | | |
| CP | $HOC^+$ | HNCO | HCOOH | $NH_2CHO$ | | $NH_2CH_2CN$ | | | | | |
| SiC | $H^2O$ | HNCS | $H_2CNH$ | $C_5N$ | | | | | | | |
| HCl | $H^2S$ | $HOCO^+$ | $H_2C_2O$ | l-$HC_4H$ | | | | | | | |
| KCl | HNC | $H_2CO$ | $H_2NCN$ | l-$HC_4N$ | | | | | | | |
| NH | HNO | $H_2CN$ | $HNC_3$ | c-$H_2C_3O$ | | | | | | | |
| NO | MgCN | $H_2CS$ | $SiH_4$ | $H_2CCNH$ | | | | | | | |
| NS | MgNC | $H_3O^+$ | $H_2COH^+$ | $C_5N^-$ | | | | | | | |
| NaCl | $N_2H^+$ | c-$SiC_3$ | $C_4H^-$ | | | | | | | | |
| OH | $N_2O$ | $CH_3$ | CNCHO | | | | | | | | |
| PN | NaCN | $C_3N^-$ | | | | | | | | | |
| SO | OCS | $PH_3$ (?) | | | | | | | | | |
| $SO^+$ | $SO_2$ | HCNO | | | | | | | | | |
| SiN | c-$SiC_2$ | | | | | | | | | | |
| SiO | $CO_2$ | | | | | | | | | | |
| SiS | $NH_2$ | | | | | | | | | | |
| CS | $H_3^+$ | | | | | | | | | | |
| HF | $H_2D^+$, $D_2H^+$ | | | | | | | | | | |
| SH | SiCN | | | | | | | | | | |
| HD | AlNC | | | | | | | | | | |
| FeO (?) | SiNC | | | | | | | | | | |
| $O_2$ (?) | HCP | | | | | | | | | | |
| $CF^+$ | $C_2P$ | | | | | | | | | | |

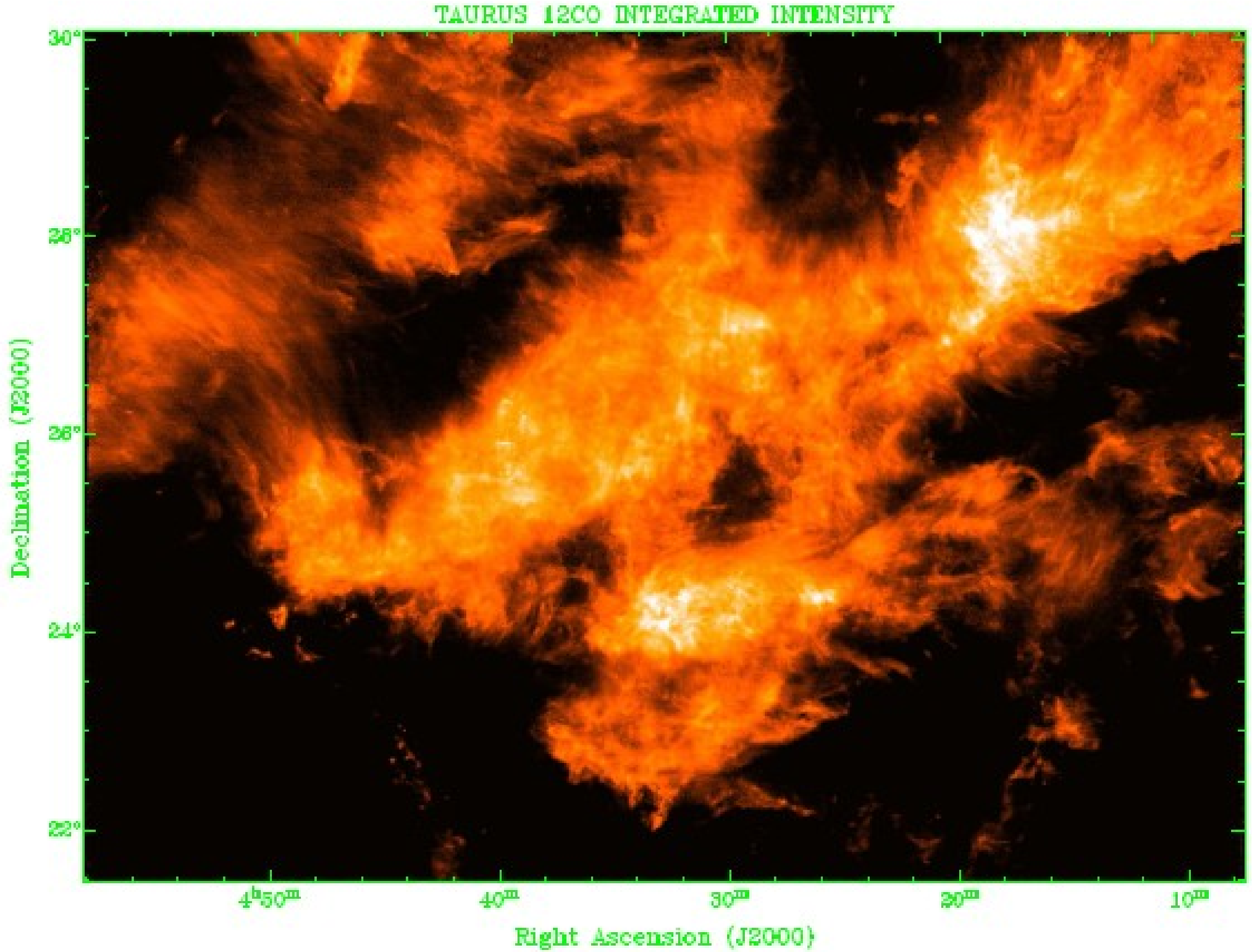
# Abundances

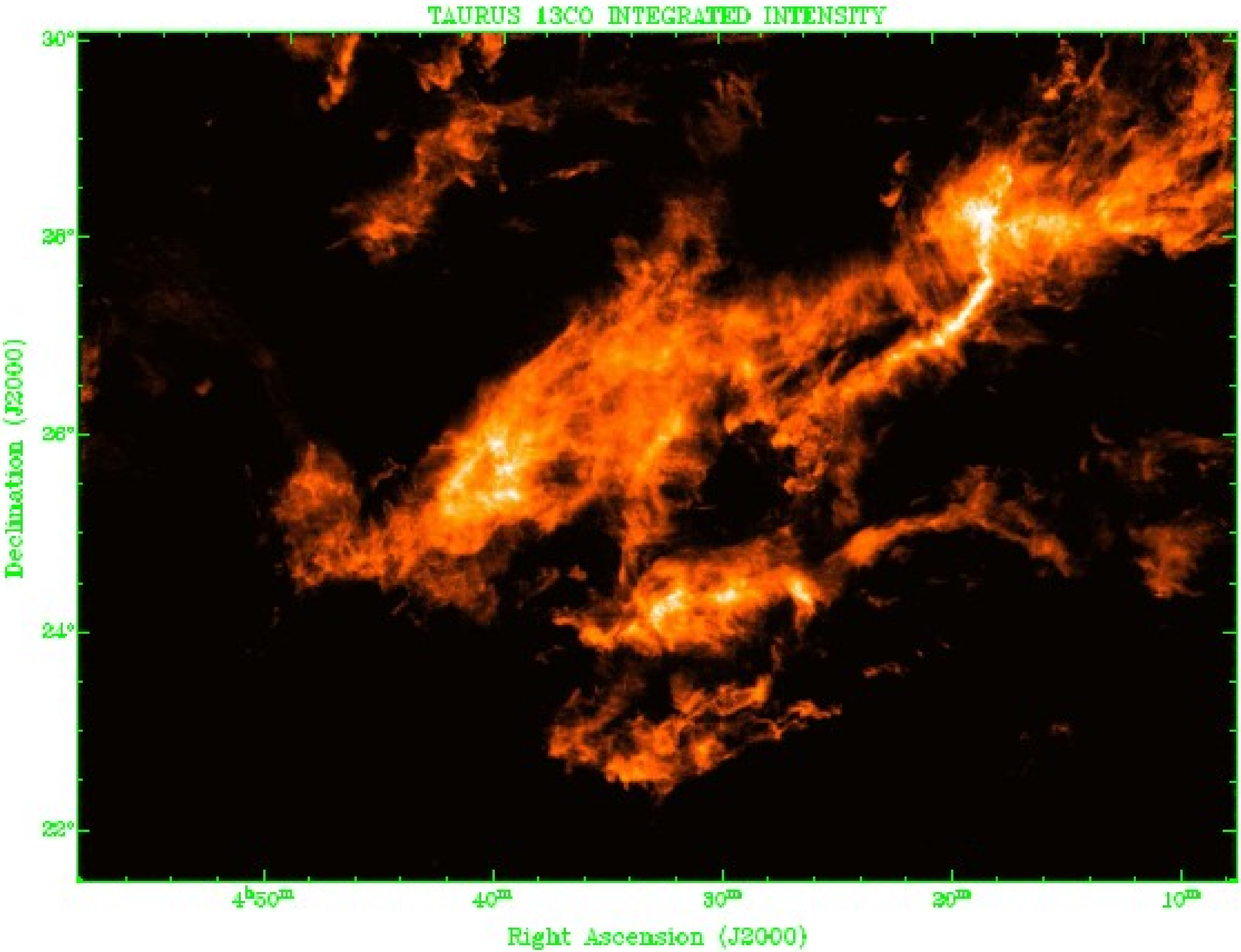
**Density profile and external UV field produce chemical gradients:**




KOSMA-$\tau$ model of a cloud with $\chi = 1, M_{\rm tot} = 100 M_\odot, n = 500$ cm$^{-3}$

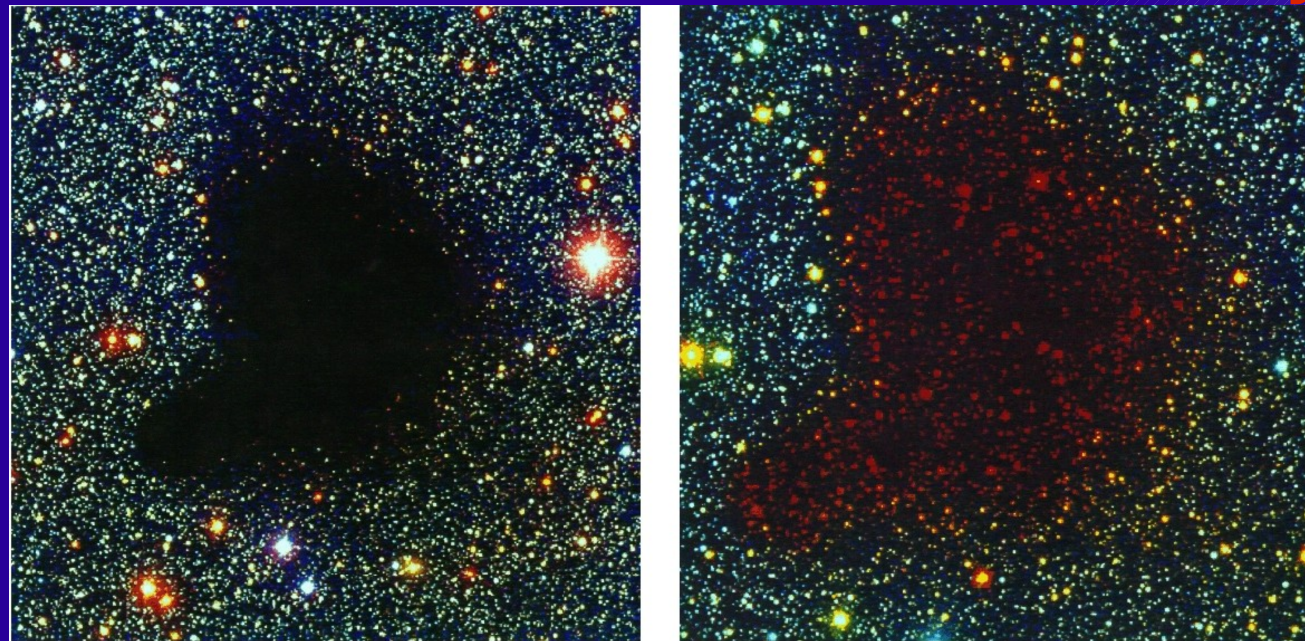
- There is no "molecular cloud". Each molecule sees a different size of the cloud.
- None of the mm/sub-mm tracers measures $H_2$. $H_2$ is molecular where many other molecules are dissociated.


TAURUS 12CO INTEGRATED INTENSITY
30°
28°
26°
24°
22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)


TAURUS 13CO INTEGRATED INTENSITY
30°
28°
26°
24°
22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)

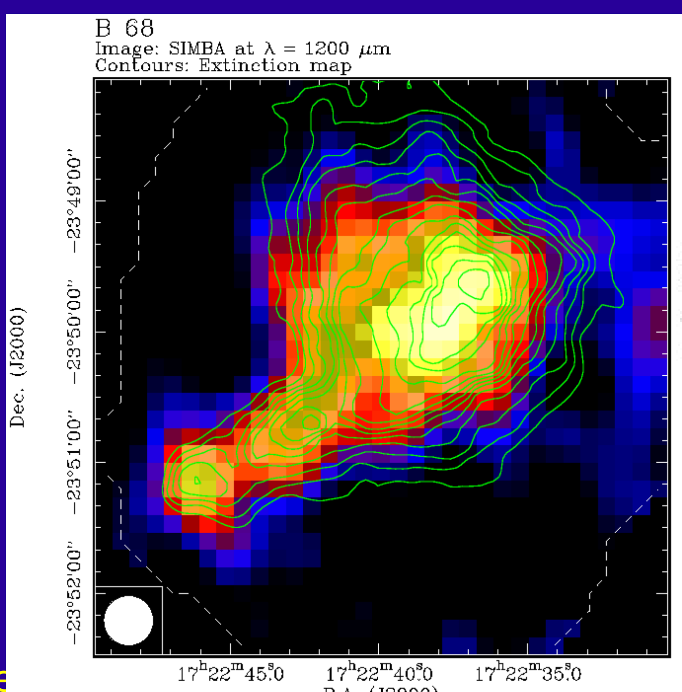
# B68: Another "hole" in the sky

Visual

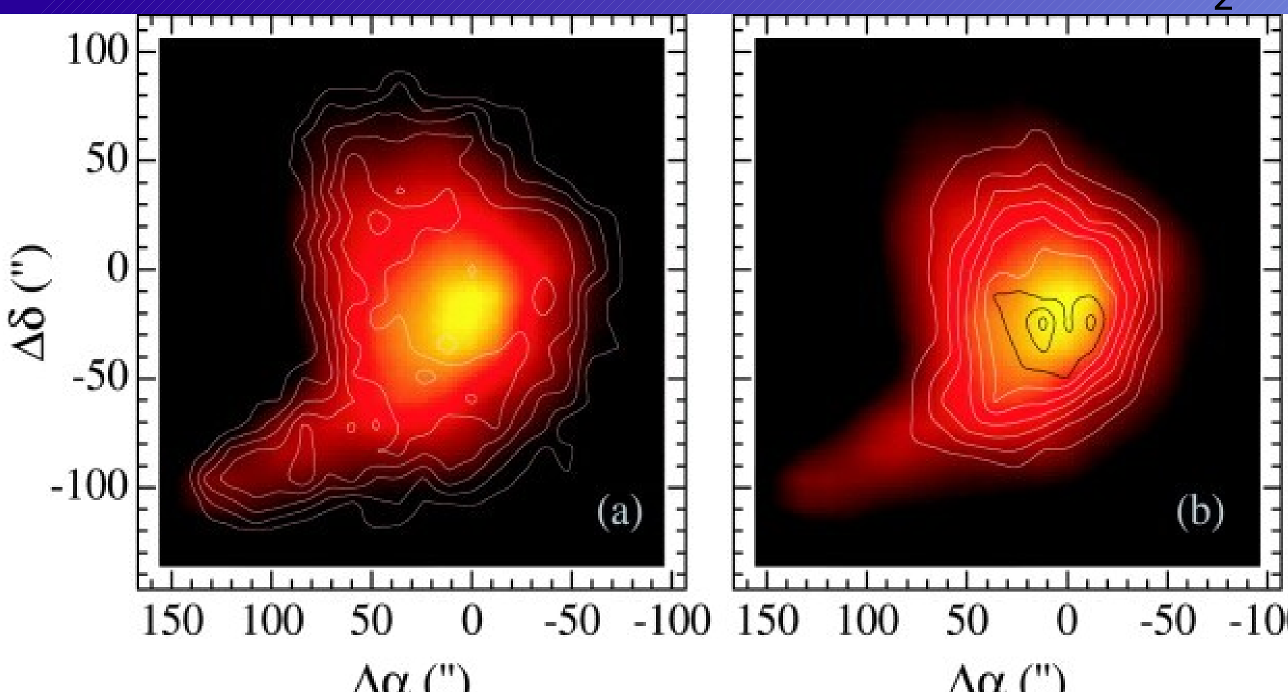


Near Infrared

1.2 mm dust continuum



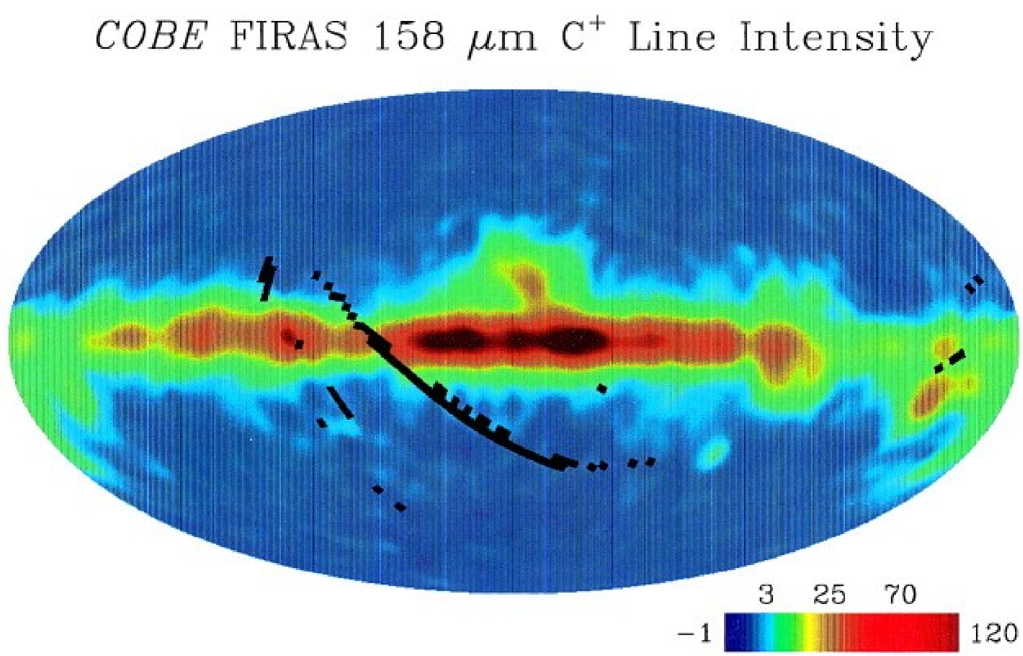

$C^{18}O$ $N_2H^+$

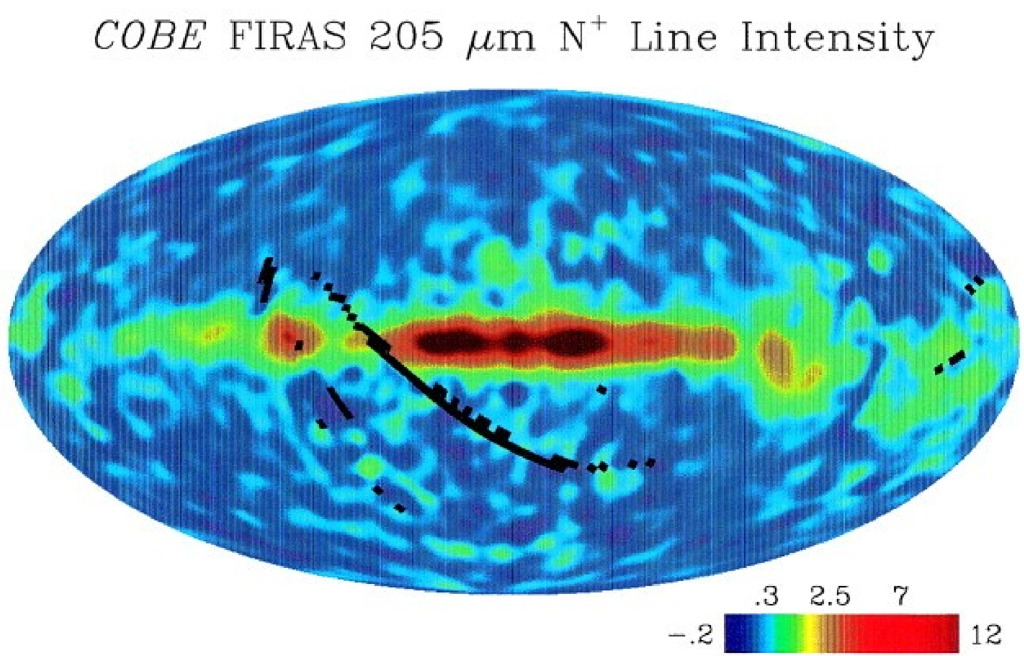


# Most important cooling lines

| Wolken | *neutral* | *ionisiert* |
|---|---|---|
| *diffus* | • **HI**: 21 cm<br>• **OI**: 2.06 und 4.74 THz<br>• **CII**: 1.90 THz | • **H**$\alpha$: 660 nm<br>• **NII**: 1.47 und 2.46 THz<br>• **OIII**: 3.39 und 5.78 THz<br>• **NIII**: 5.23 THz |
| | *kalt* | *warm* |
| *dicht* | • **CO**: Linien aller 0.12 THz<br>• **CI**: 0.49 und 0.81 THz<br>• **CH**: 0.54 THz | • **CO**: Linien aller 0.12 THz<br>• **CI**: 0.49 und 0.81 THz<br>• **CH**: 0.54, 1.66 und 2.58 THz<br>• **OH**: 2.51 THz<br>• **$H_2O$**: viele Linien $\nu > 1$ THz<br>• **Staub**: Kontinuum |

# Most important cooling lines




CII and NII from the diffuse ISM and bright HII regions around young stars