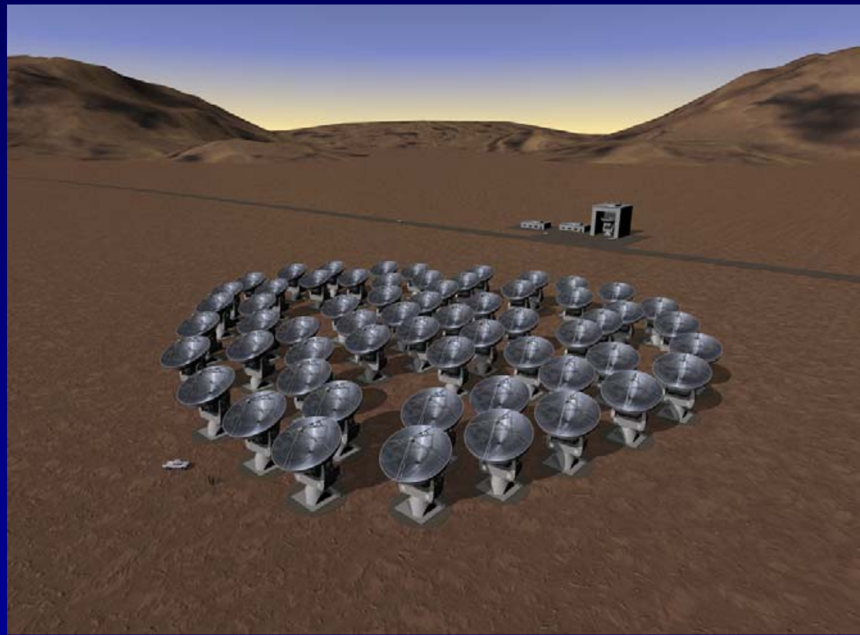
ALMA and chemistry



Ewine van Dishoeck, May 8 2006
Aarhus

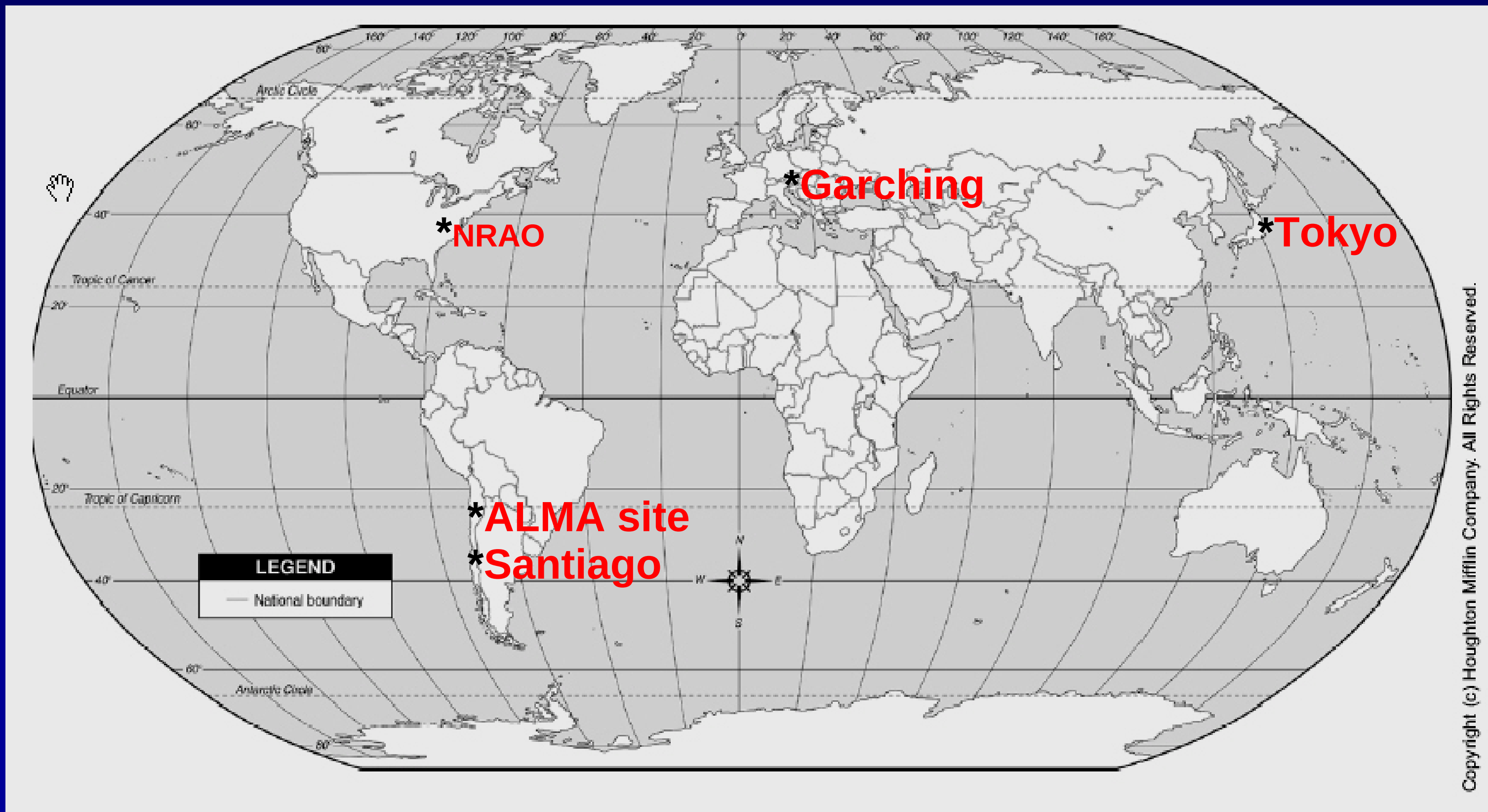
What is ALMA?

- **50 x 12m antenna's (64 goal); 7238 m^2 total area**
  - **Factor ~10 larger than existing arrays**
  - **ACA of 12x7m + 4 12m TP dishes to be provided by Japan**
- **Millimeter/submillimeter wavelengths**
  - **7 – 0.35 mm (30-900 GHz)**
- **Zoomlens capability**
  - **Configurations from 150 m to 14 km**
  - **High spatial resolution: $(0.25''/B_{km})\lambda_{mm}$**
    - **0.08" at 1mm with 3 km baselines**
    - **0.01" at 0.35 mm with 14 km baselines**
- **High (5000 m) dry site in northern Chile**

⇒ALMA will be 500-10,000 times faster and will see 50 times sharper than existing millimeter facilities; as sharp as the VLT and Hubble!

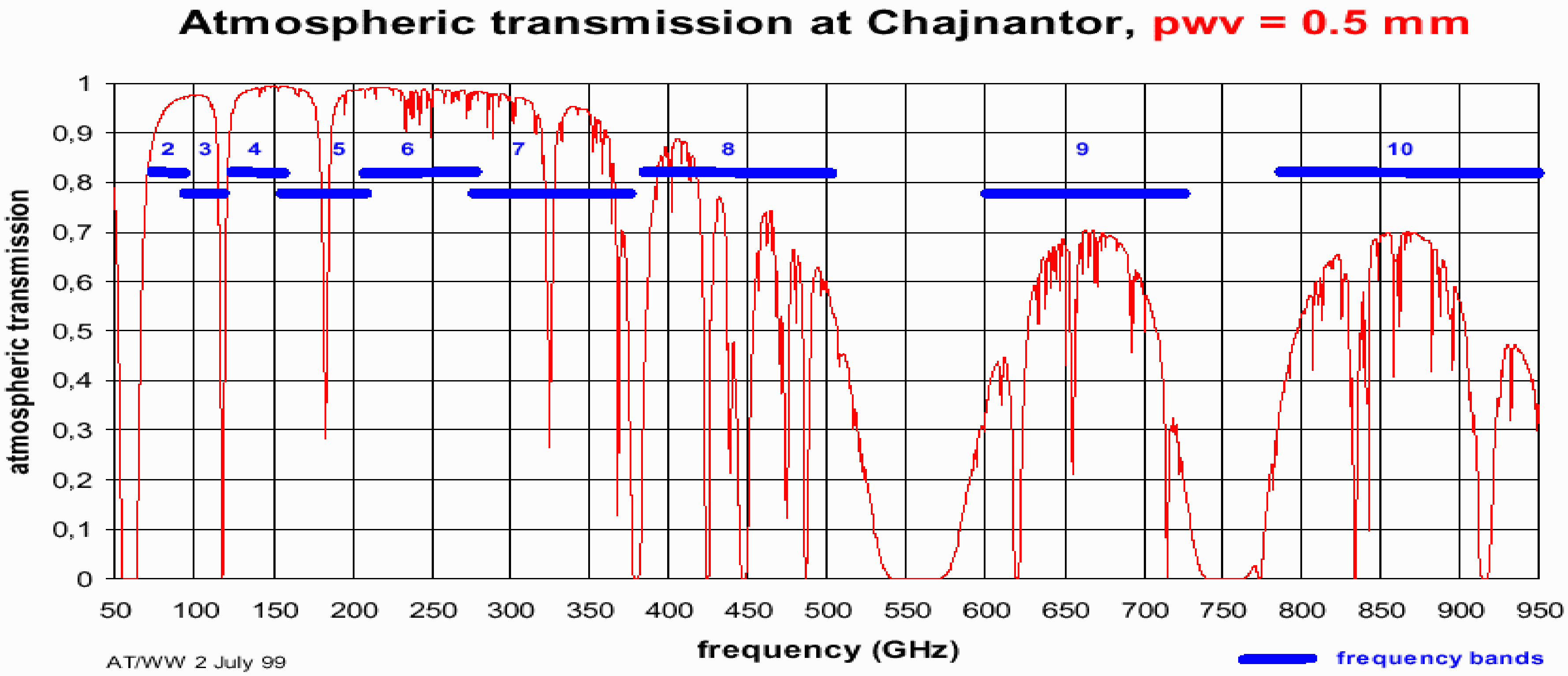
ALMA is a world array

- Europe – North America bilateral project signed in 2003
- Japan joined provisionally 2004 with enhancements to bilateral project; to be finalized in 2006



ALMA is happening!

ALMA Receiver Bands



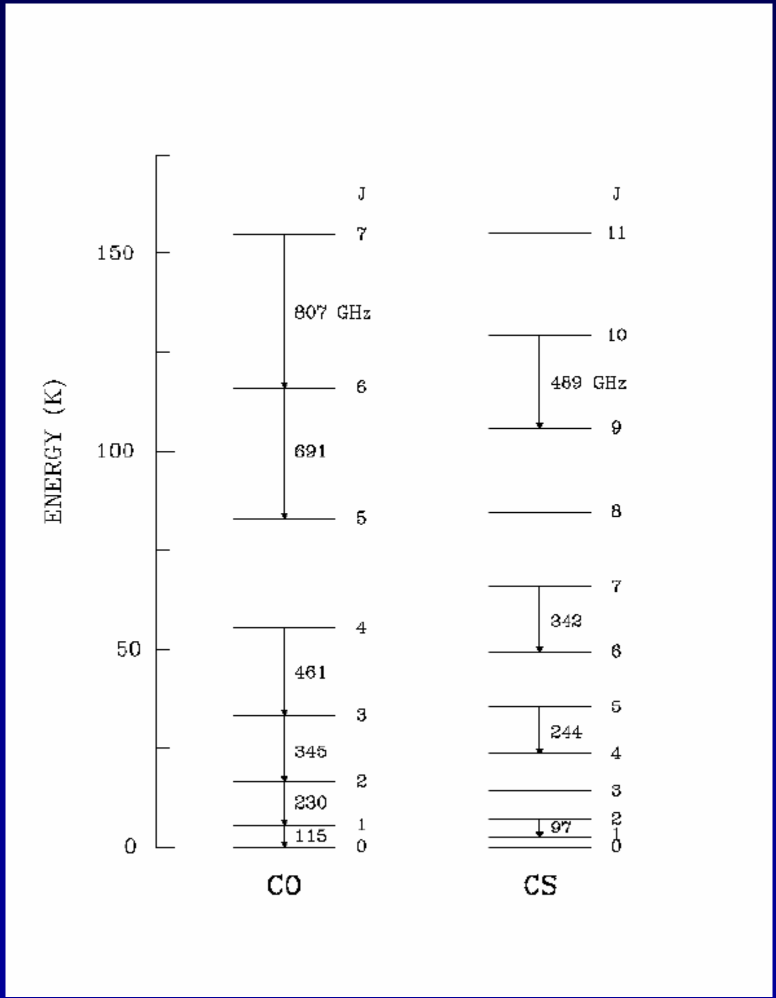
Bands 3, 6, 7 and 9 installed initially

Bands 4, 8 and 10 (TBC) to be provided by Japan

Radiation at (sub)mm wavelengths

- **Continuum: cold dust at 10-100 K; steep spectrum with ν^3**
- **Lines: pure rotational transitions of molecules**

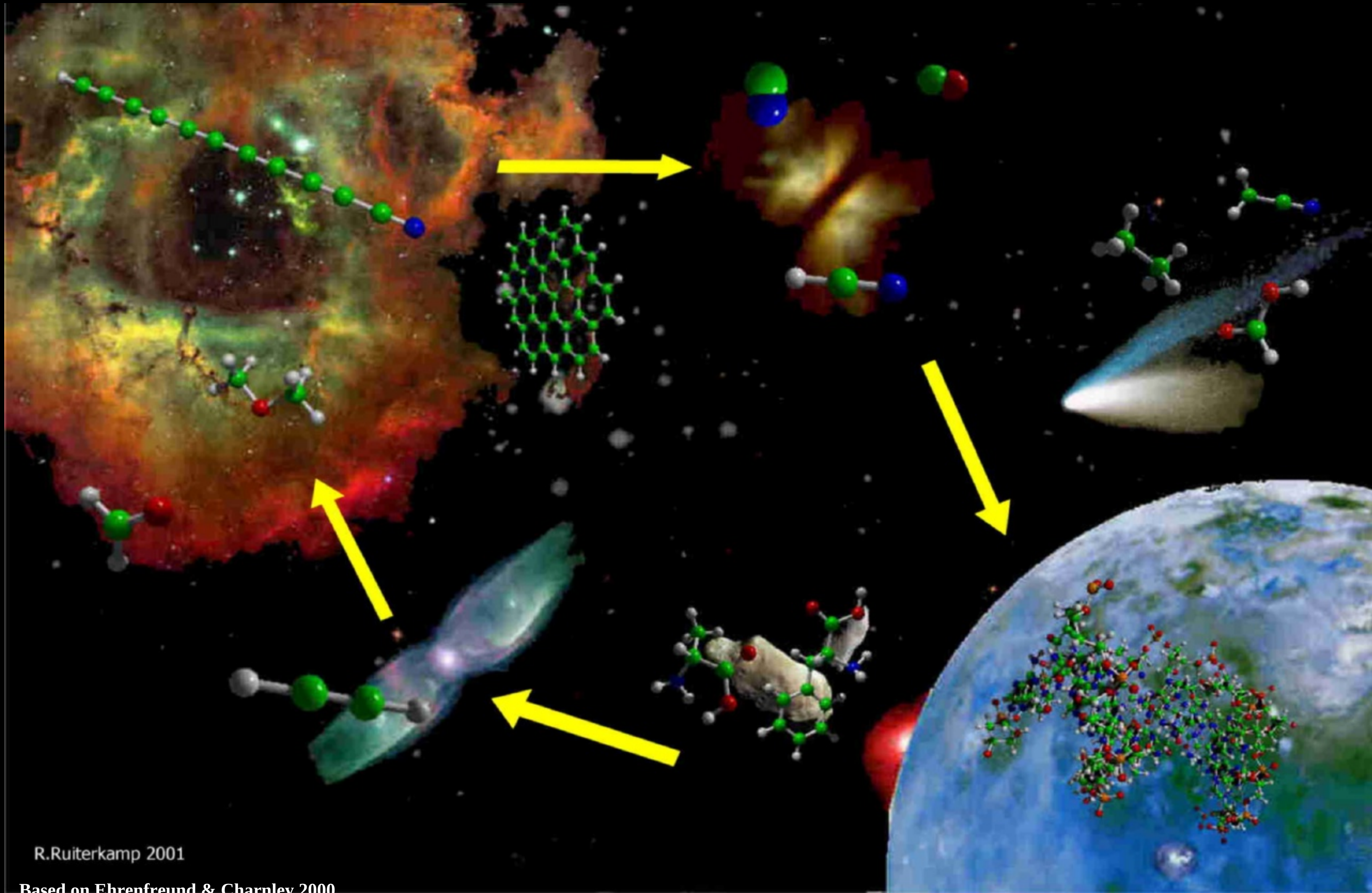
➡ ***ALMA probes both cold and warm gas***



Why chemistry

- *Astrochemistry:* discovery of exo-planets and interest in formation of planetary systems has provided new focus to astrochemistry:
  - What is composition of gas and solids at different stages of star- and planet formation?
  - What fraction of this material is incorporated into new solar systems?
- *Molecular astrophysics:* use molecules and dust as diagnostics of highly extincted star- and planet-forming regions:
  - What is temperature, density and velocity structure?
  - Chemical diagnostics of different stages or components (e.g., outflow, infall, disk, …)?
- *Unique chemical laboratory*

ALMA and Astrochemistry



Lifecycle of gas and dust; raw material for planetary systems

How to form complex molecules
1. Grain surface formation

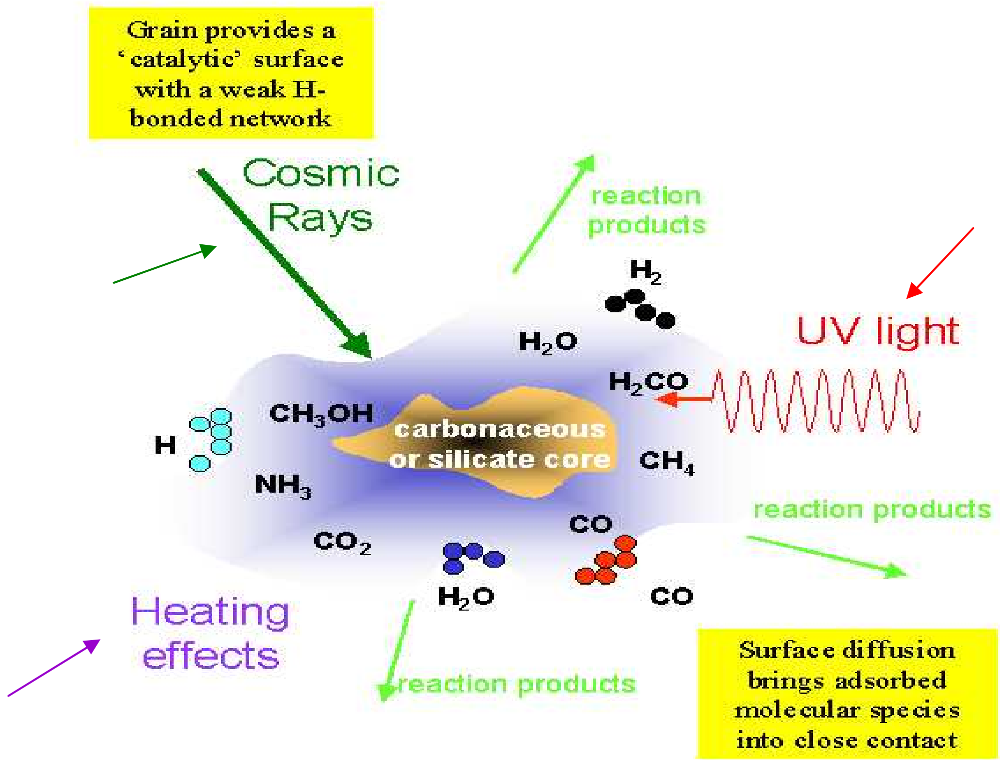
- **Heavy freeze-out of molecules onto grains in cold pre-stellar phase**
- **Grain surface reactions produce new species (*first generation*)**

$$\text{O, C, N, CO} \xrightarrow{\text{H}} H_2O,\ CH_4,\ NH_3,\ H_2CO,\ CH_3OH$$

$$\text{CO} \xrightarrow{\text{O}} CO_2$$

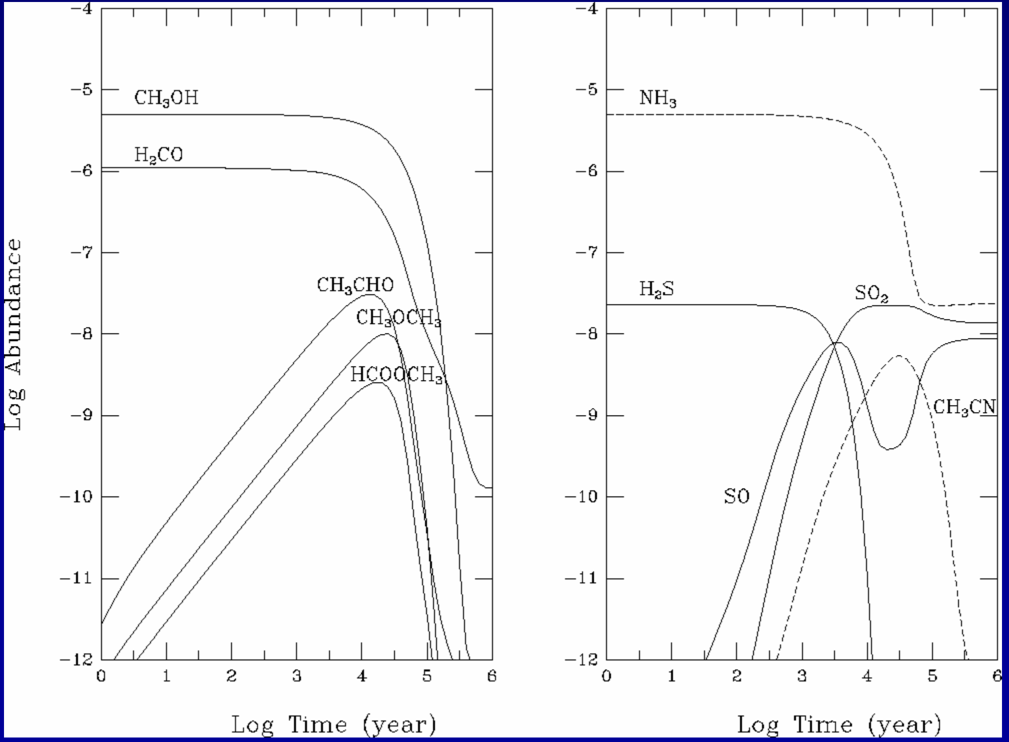
Ice processing => complex organics

- Heating, UV radiation, … can modify ice composition



2. High-*T* gas-phase chemistry

- **Evaporated molecules (i.p. CH_3OH) from grains react in high-T gas to form more complex species for period of 10^4-10^5 yr (*second generation*)**



Major questions

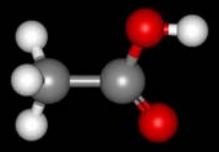
- Which molecules are produced on grains and which are due to “second generation” gas-phase chemistry?
- How far does chemical complexity go?
  - Large organic molecules near YSOs
  - Grain formation in AGB shells
  - ……
- Time scales and mechanisms of various processes
- Dependence on mass, luminosity, ….. of object?

Why spectral surveys?

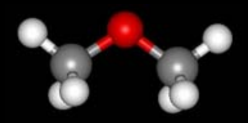
- Unbiased census of molecules in all phases of lifecycle
  - Diffuse clouds => protostars => hot cores + PDRs =>disks => AGB envelopes => PN => SN
  - In regions with heavy line confusion, surveys essential for identification
- Constrain physical structure (*T*,*n*)
- Dynamical processes per species per line
  - Shocks, infall, outflow, rotation, turbulence, …
- Measurement of cooling rate gas
- Measurement of contributions line to continuum
- Search for new (exotic) species

Some complex organic molecules

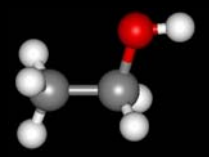
Detected



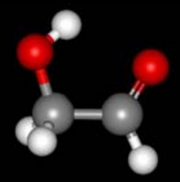
Acetic acid



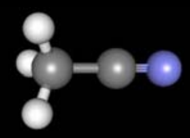
Di-methyl ether



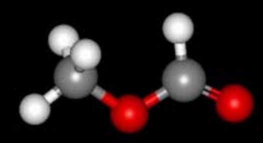
Ethanol



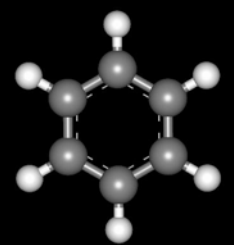
Sugar



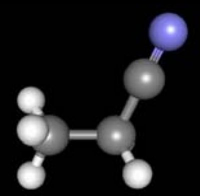
Methyl cyanide



Methyl formate

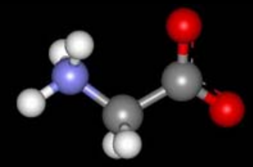


Benzene

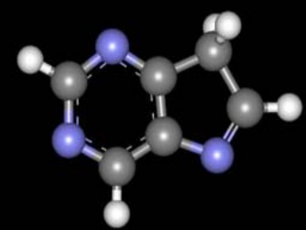


Ethyl cyanide

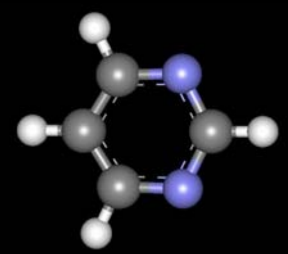
Not (yet) detected



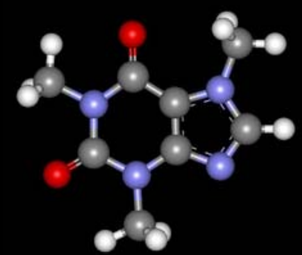
Glycine



Purine



Pyrimidine



Caffeine

Based on Ehrenfreund 2003

History surveys

- **Most early mm line surveys focussed on Orion-KL and Sgr B2**
  - **Inventory of lines and spectra in ~1' beams**
- **Orion-KL 1 mm survey by Blake et al. (1985-1987) most influential because data accompanied by**
  - ***Physical analysis*: different components in 30" beam: hot core, compact ridge, plateau, quiescent ridge**
  - ***Chemical analysis*: complexity of spectra caused by interaction young stars with surroundings through shocks, heating, UV photons, varying C/O ratios?**

Caltech 230 GHz survey

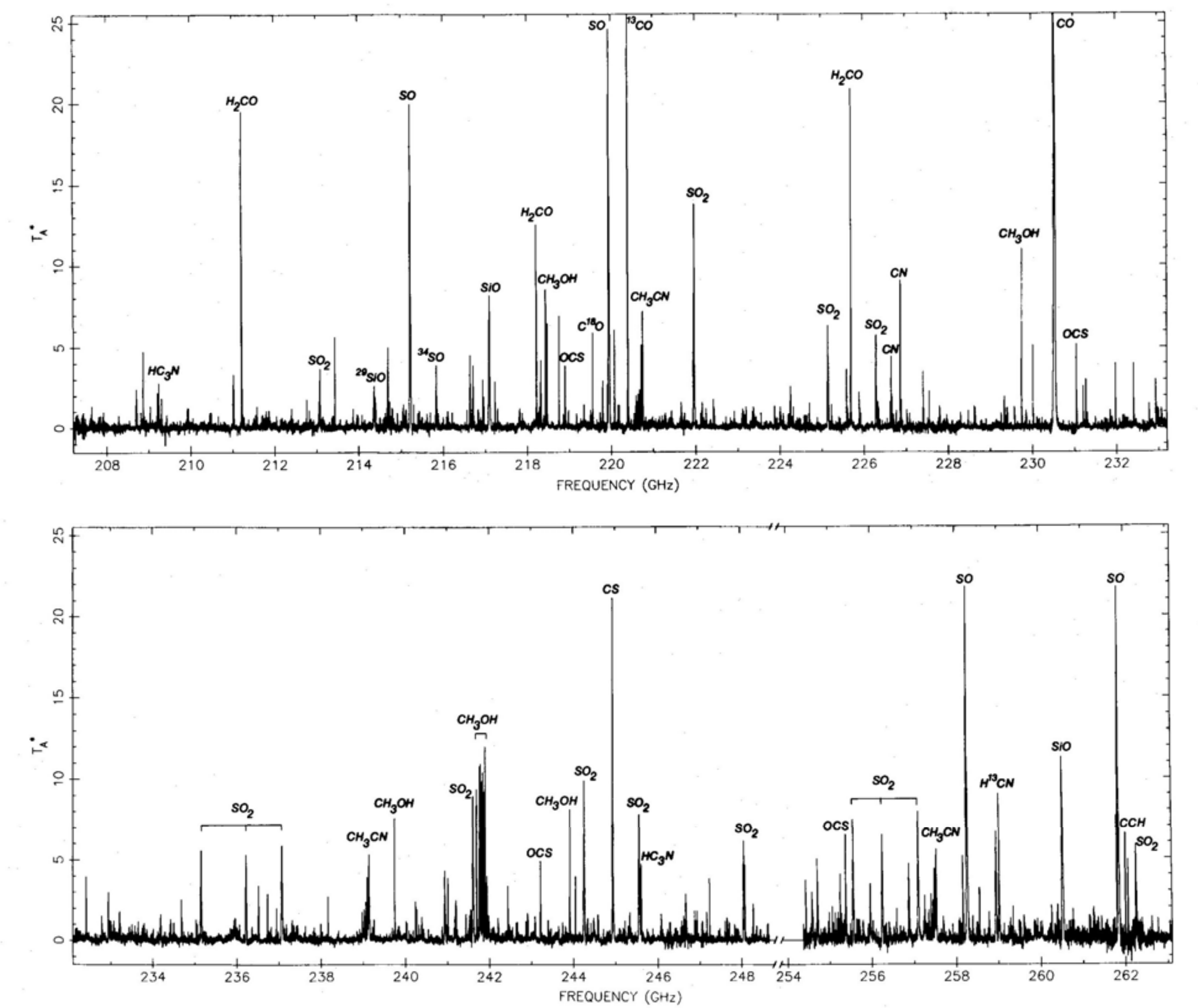


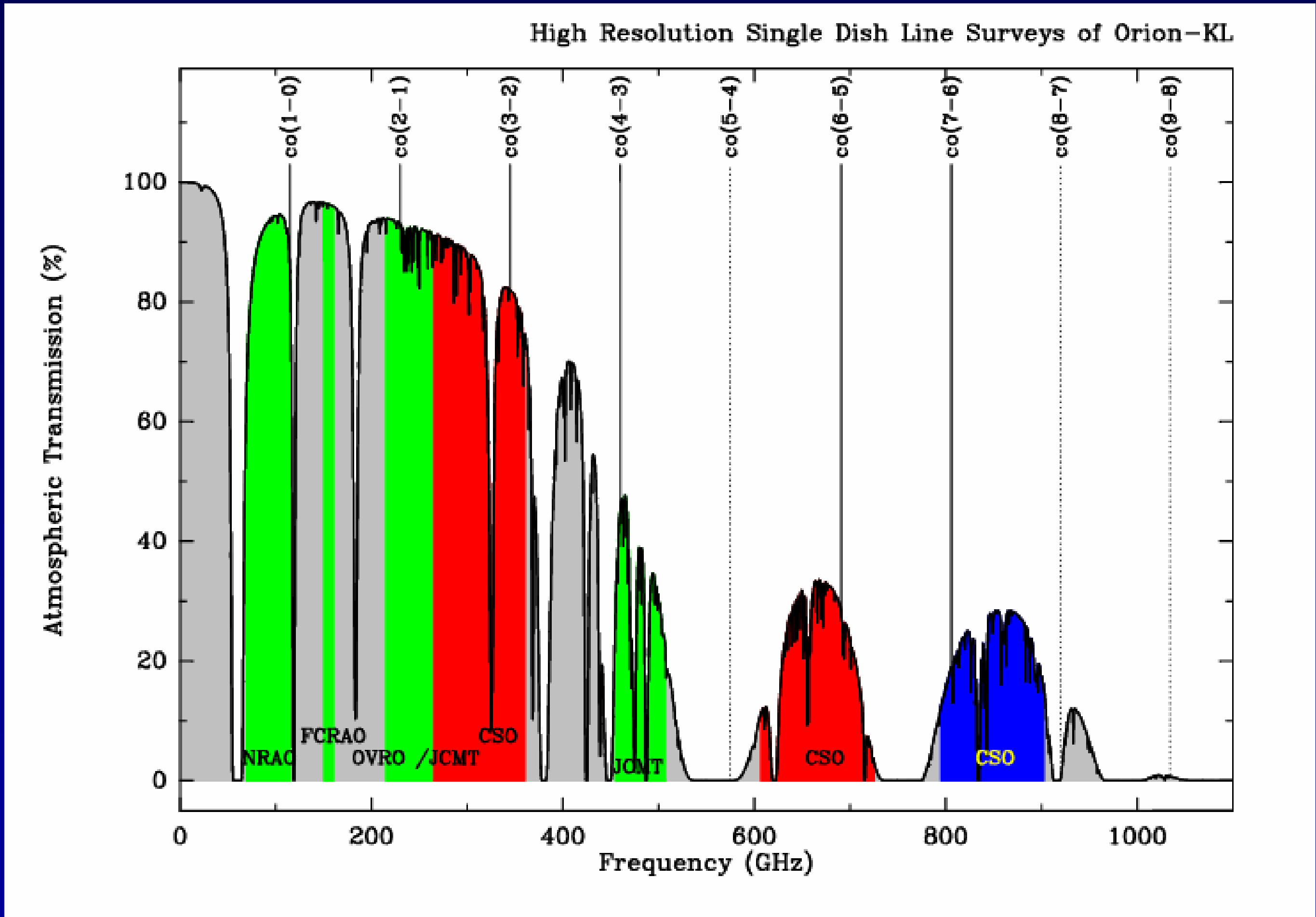
FIG. 1.—Compressed view of the OVRO spectral line survey of OMC-1

Sutton et al. 1985
Blake et al. 1986
Blake et al. 1987

Recent surveys

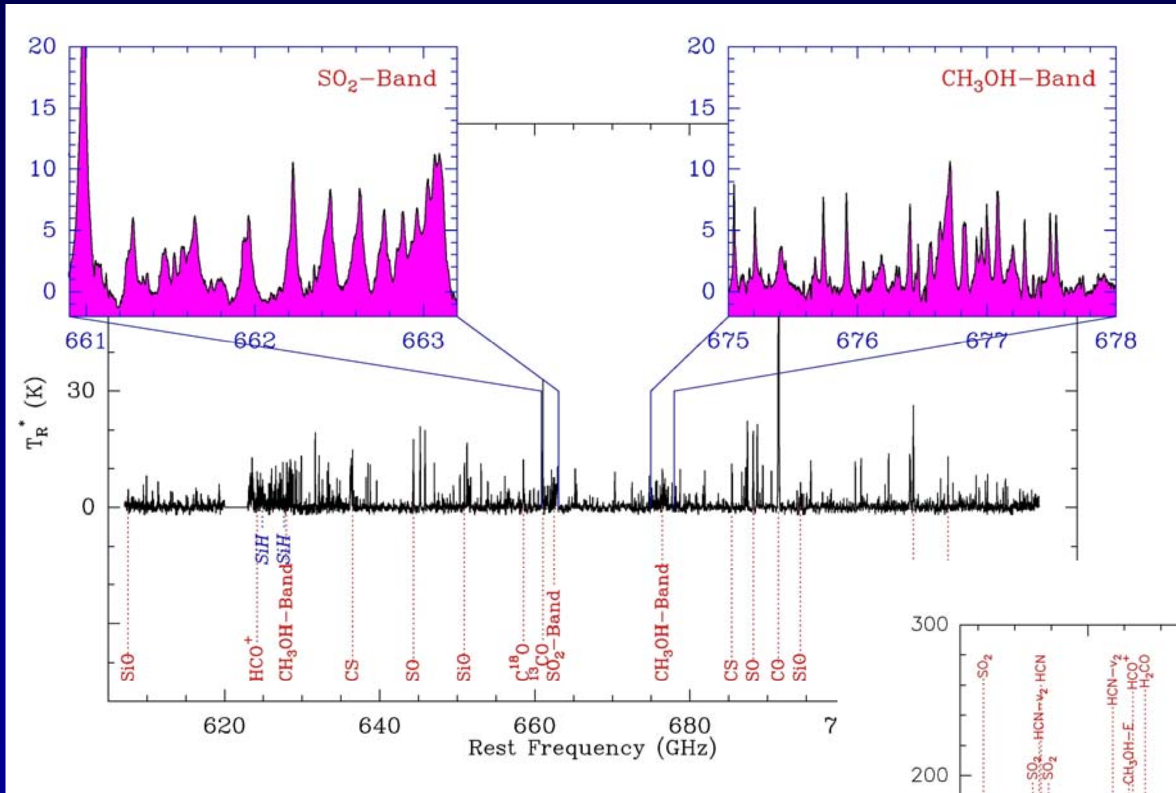
- Several recent surveys in 150-850 GHz windows (2 mm – 350 μm) atmospheric windows from ground
  - Smaller beams 10”-30”
  - Probe higher excitation lines => warmer + denser gas associated with YSO/AGB rather than extended cloud
  - Improved sensitivity receivers => larger variety of objects surveyed
    - Partial line surveys: O.K. for not too crowded sources

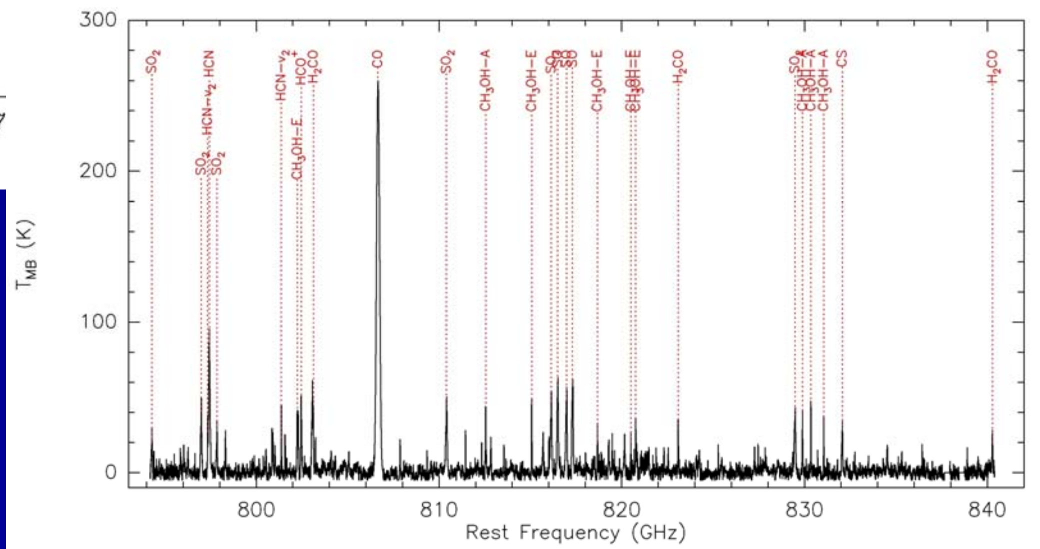
Line surveys of Orion-KL



Schilke 2005

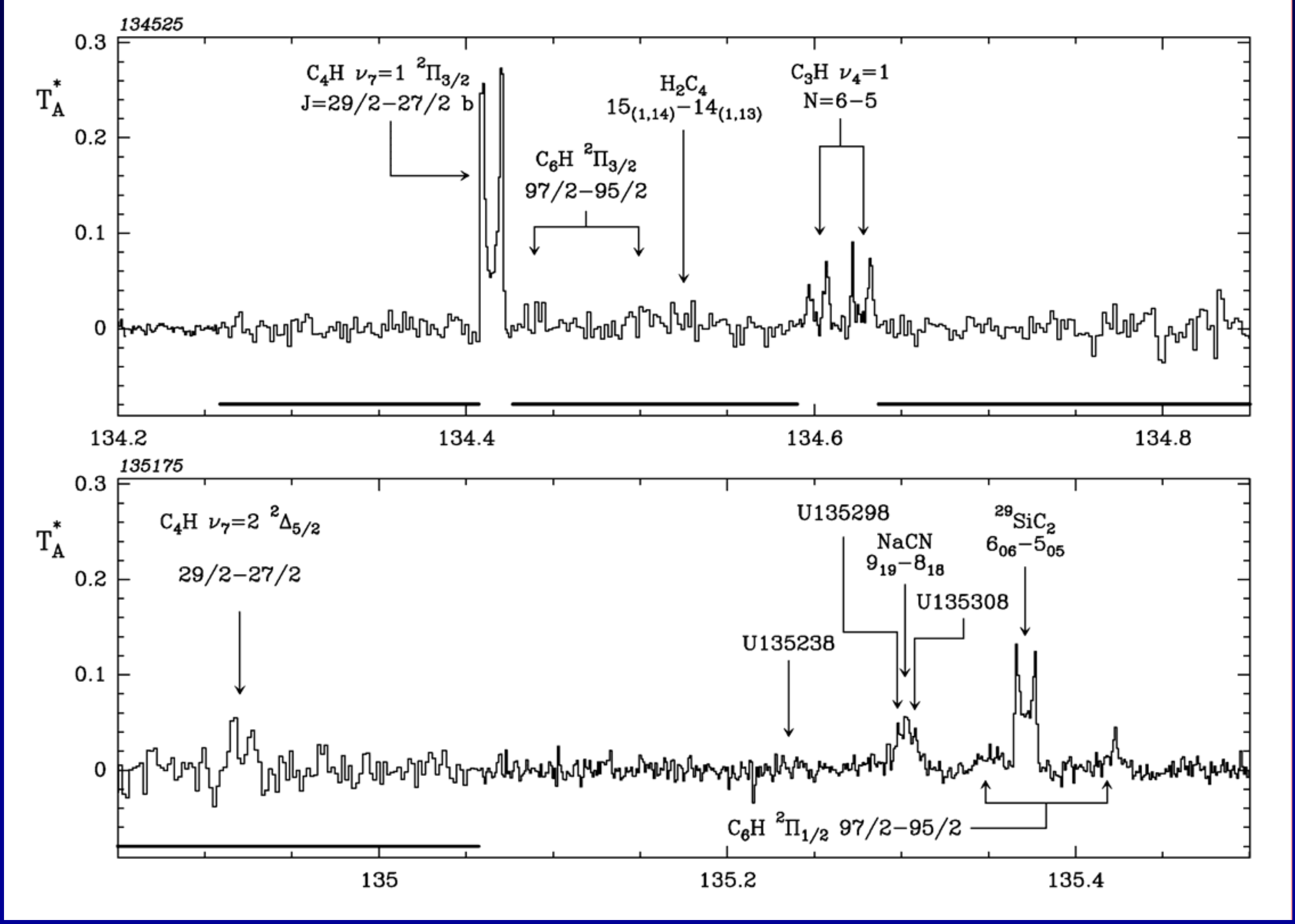
CSO 650 and 850 GHz surveys





Schilke et al. 2001
Comito et al. 2005

Evolved star surveys: IRC +10216



Cernicharo et al. 2000

Results

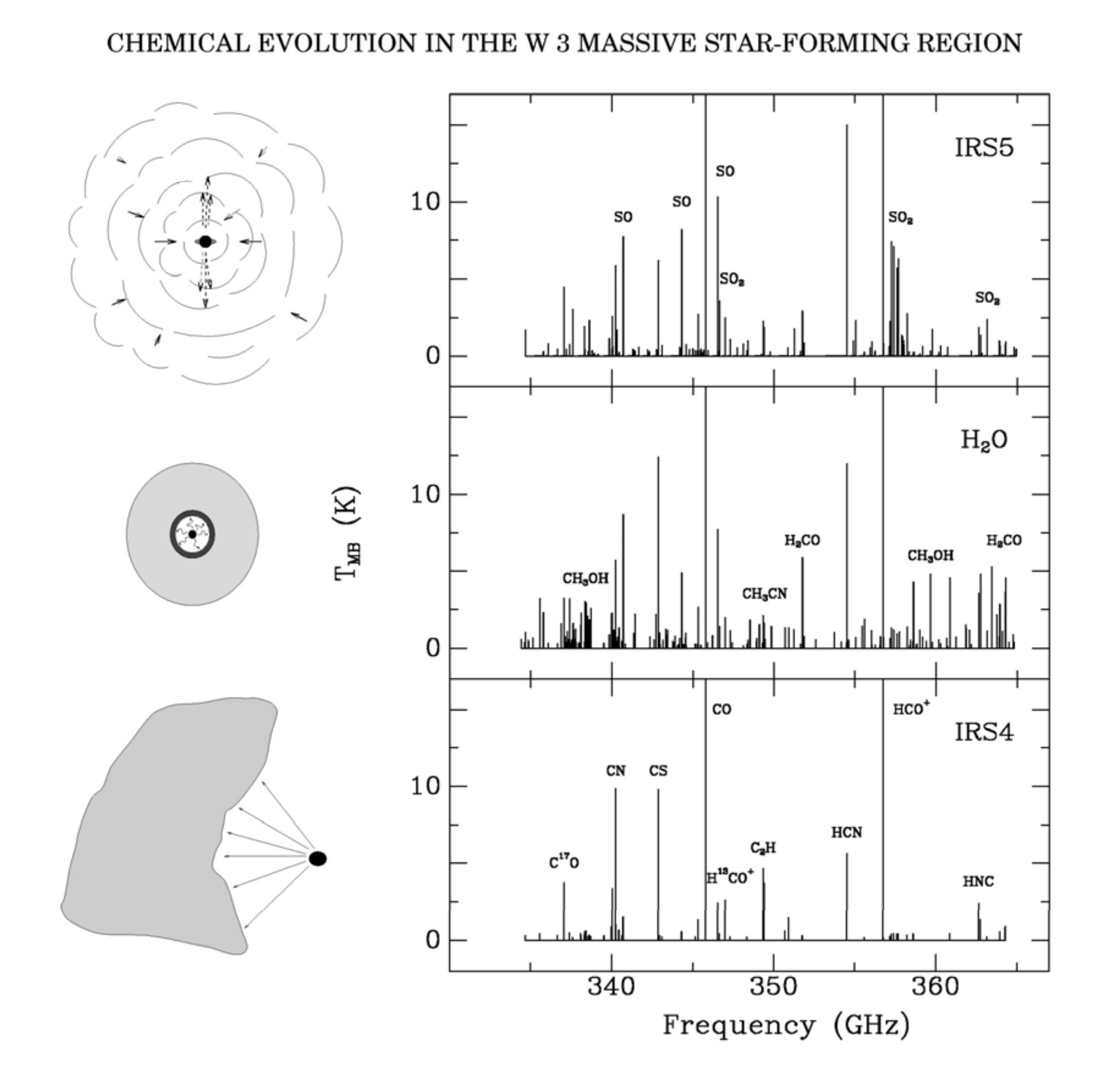
- **Great technical achievement**
- **Lines can contribute >50% of broadband continuum at 350-650 GHz in *some* objects**
- **Often several physical and chemical components in beam**
  - **Separated on basis of excitation and line profiles?**
- **Most of diagnostic information is in *weak* features => need *deep* surveys**
- **Development line data bases and line survey software**

But what have we learned?

- Chemical composition sensitive to evolutionary state object
  - Line-rich vs. line-poor sources
- Low-mass YSOs can have as complex chemistry as high-mass YSOs
- Chemical segregation on small scales
  - Mostly from interferometers
- …..

Line rich vs line poor sources

Three massive YSOs in W3



JCMT 345 GHz

IRS5:
Rich in SO, SO_2, …

H_2O:
Rich in complex mol.

IRS4:
Simple, PDR species

Helmich & vD 1997

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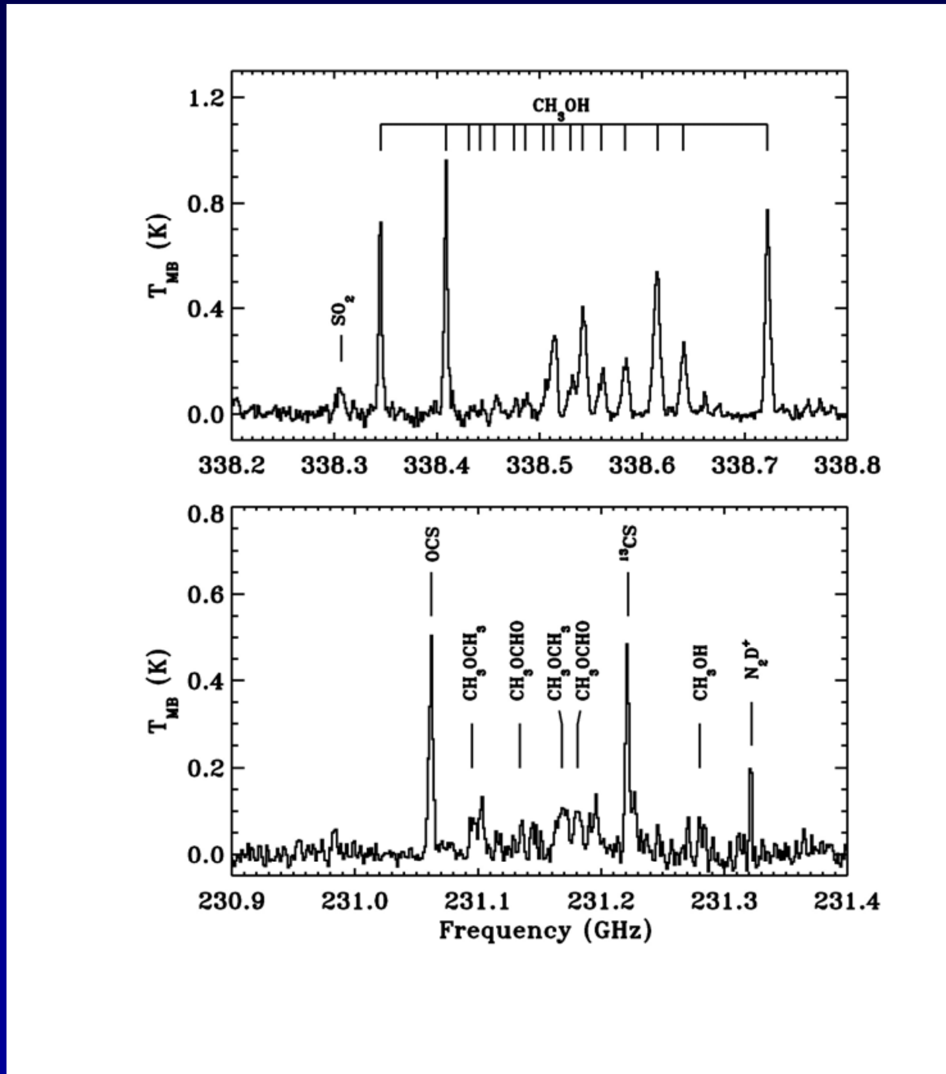
Complex organics around solar-mass protostars



IRAS 16293-2422

JCMT

Hot CH_3OH gas

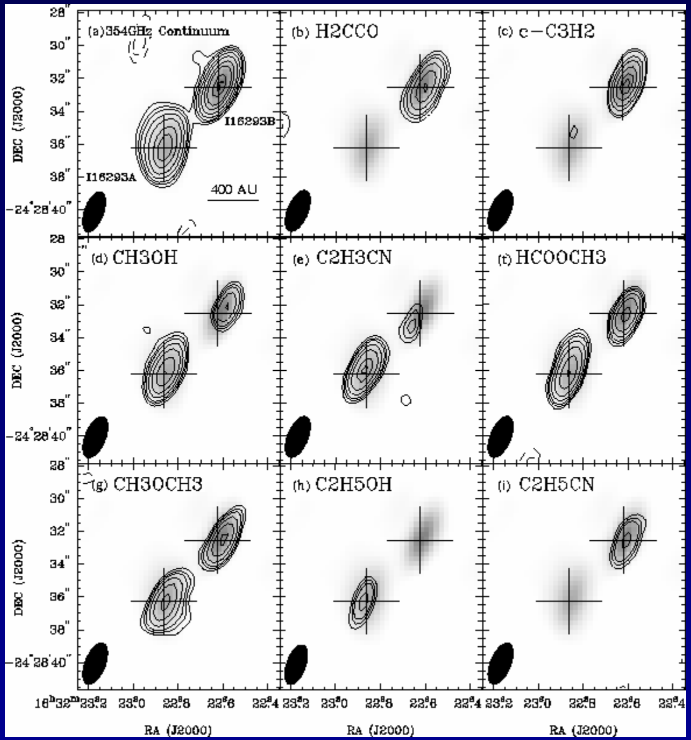
T_{ex}~80 K

vD et al. 1995, Ceccarelli et al. 2000

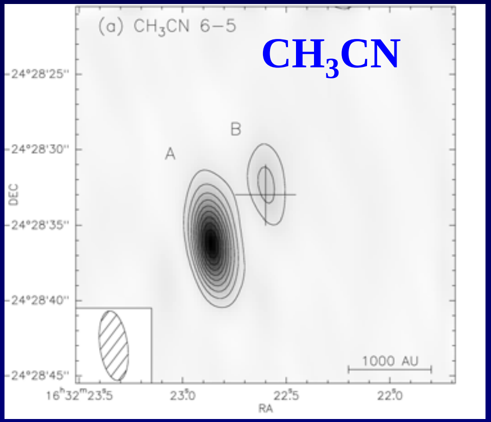
Cazaux et al. 2003, Bisschop et al. , unpl., Caux et al. in prep.

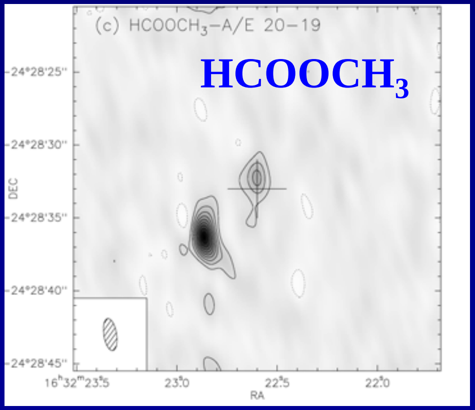
Starting to image low-mass hot cores

IRAS 16293 protobinary



Kuan et al. 2004, SMA
Chandler et al. 2005, SMA
Schöier et al. 2004, OVRO

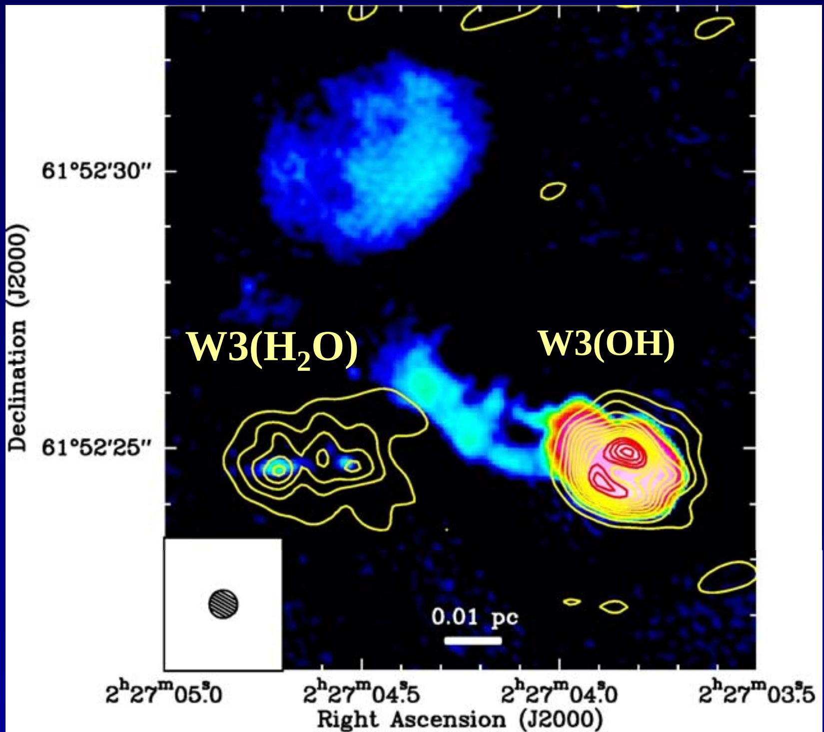


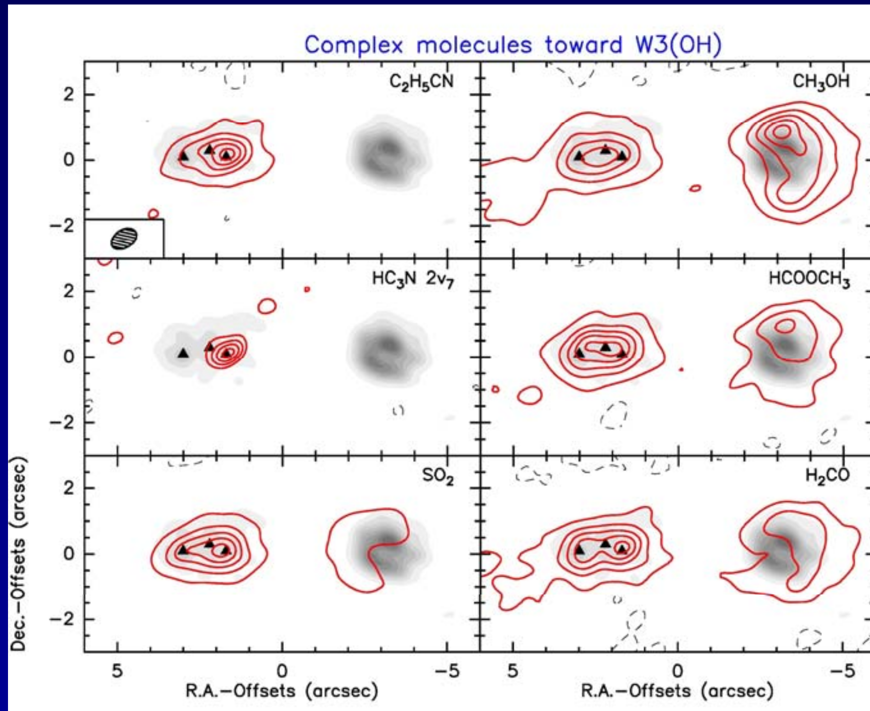


Bottinelli et al. 2004, PdB

Chemical differentiation found on small (few hundred AU) scales

W 3 small scale structure





- Note chemical differentiation between O- and N-rich complex organics on few arcsec scale (few thousand AU)

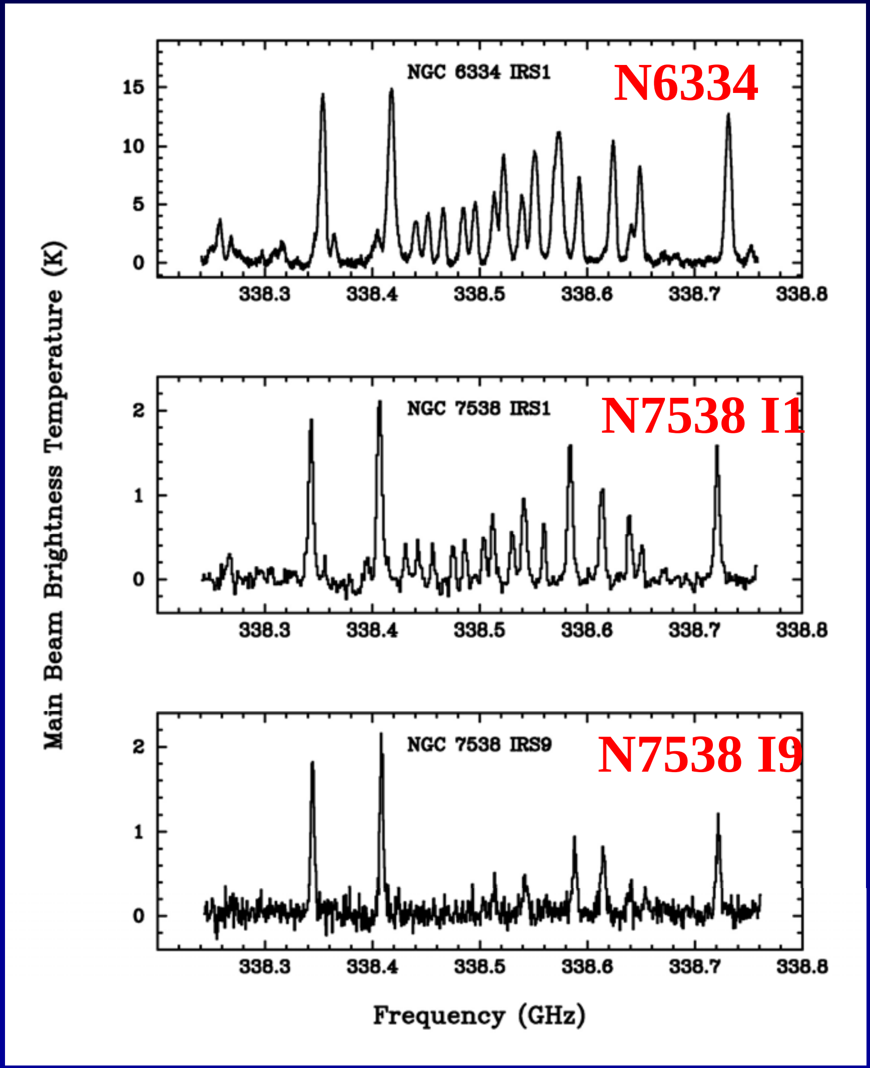
Wyrowski et al. 1999

But what have we learned?

- Chemical composition sensitive to evolutionary state object
  - Line-rich vs. line-poor sources
- Low-mass YSOs can have as complex chemistry as high-mass YSOs
- Chemical segregation on small scales
  - Mostly from interferometers
- Abundance profiles
  - Hot vs. cold molecules
  - Jump, drop abundance profiles

Hot and cold methanol

CH_3OH 7_K-6_K band



Hot:
200 K

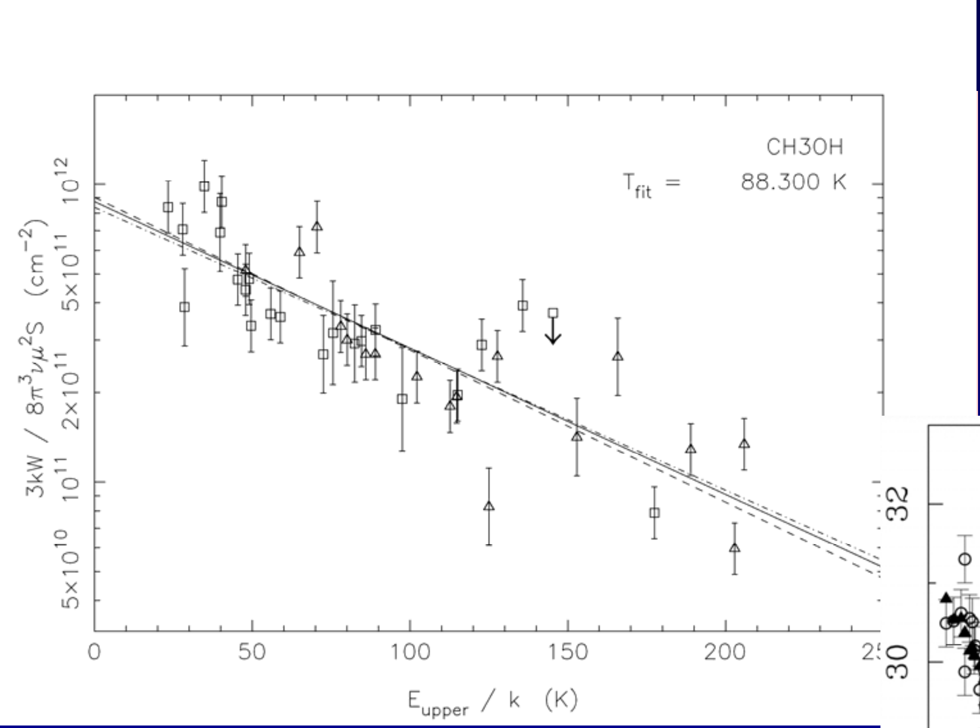
Warm:
100-200 K

Cold:
30 K

Van der Tak et al 2000

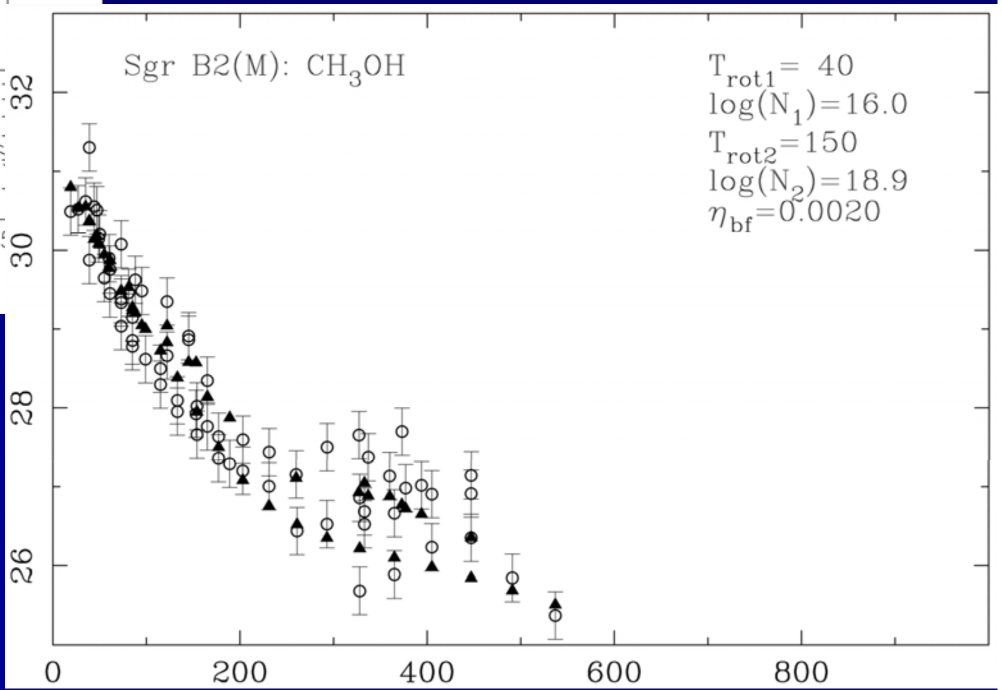
Rotation diagrams

IRAS16293-2422: one temperature



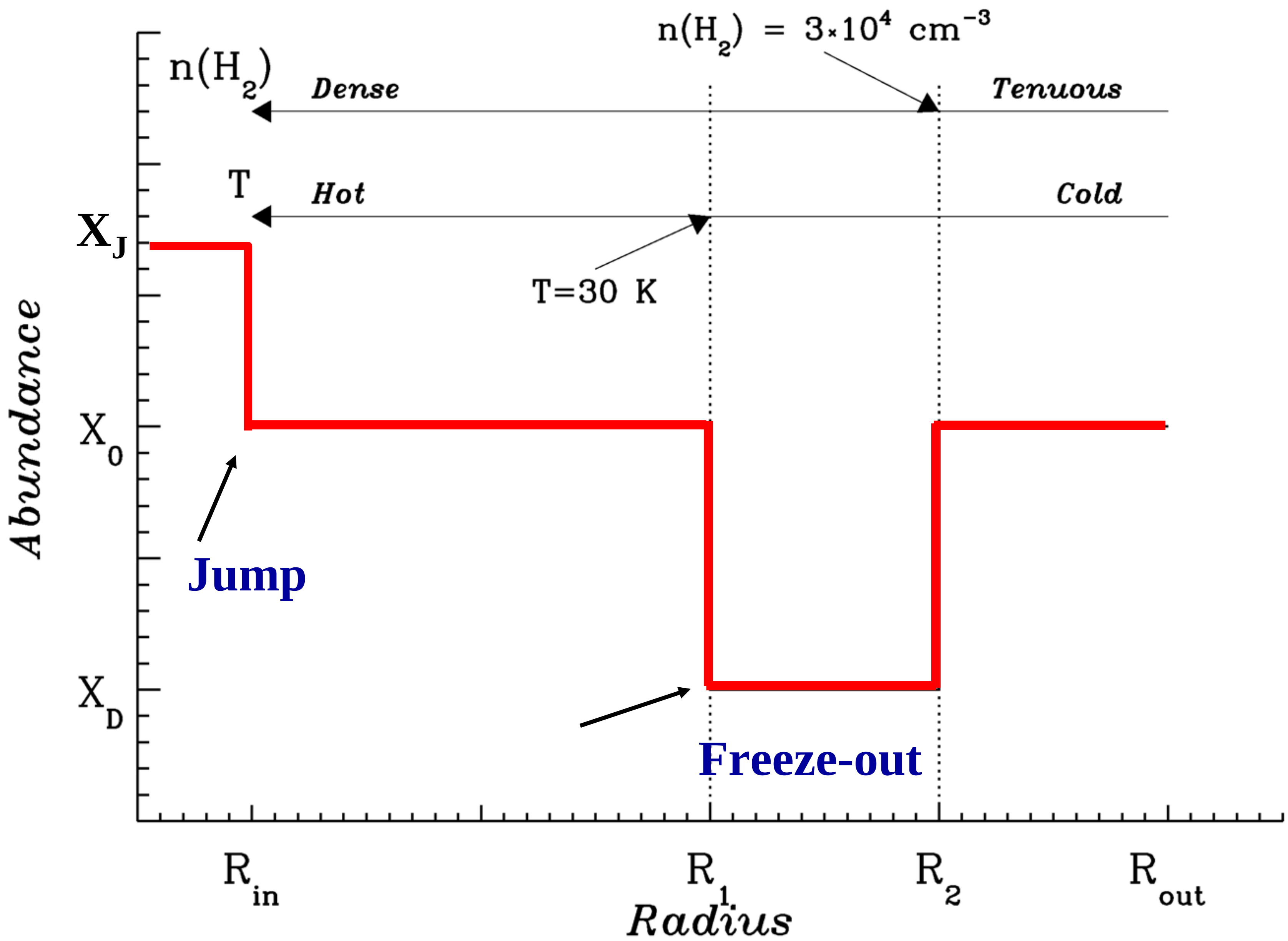
vD et al. 1995

SgrB2(M): two temperatures



Nummelin et al. 2000

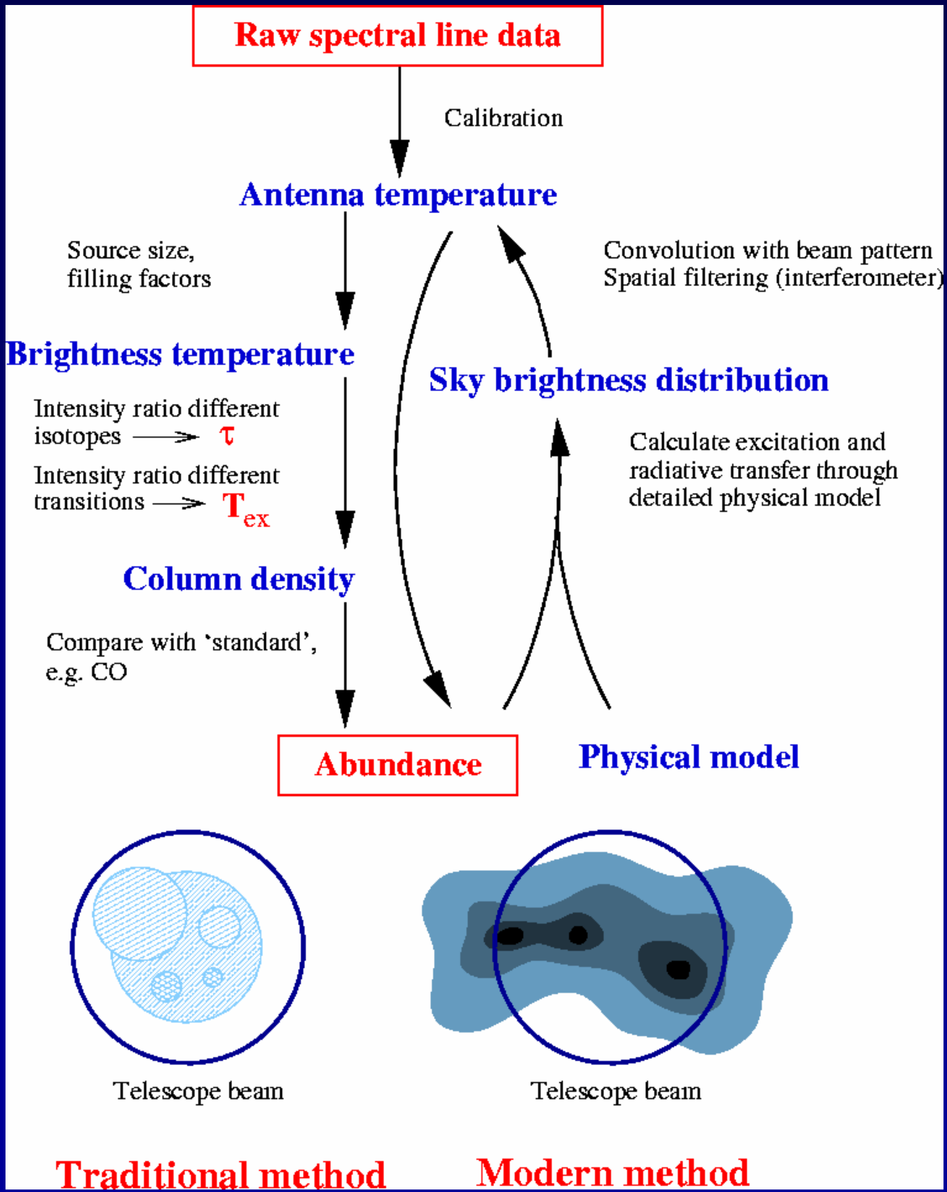
Example: CH_3OH jump abundance structure



Single dish observations do not reolve this structure!

Jørgensen et al. 2004, 2005

Derivation of molecular abundances



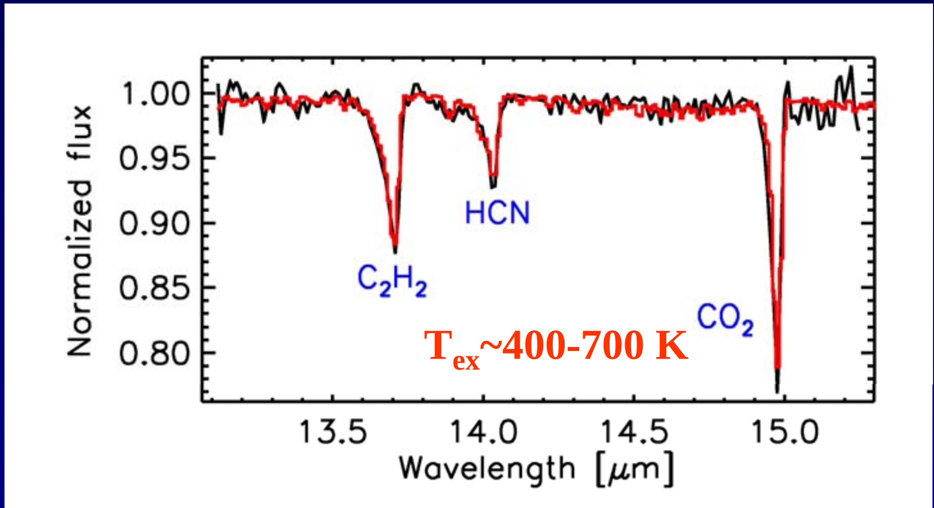
Why ALMA?

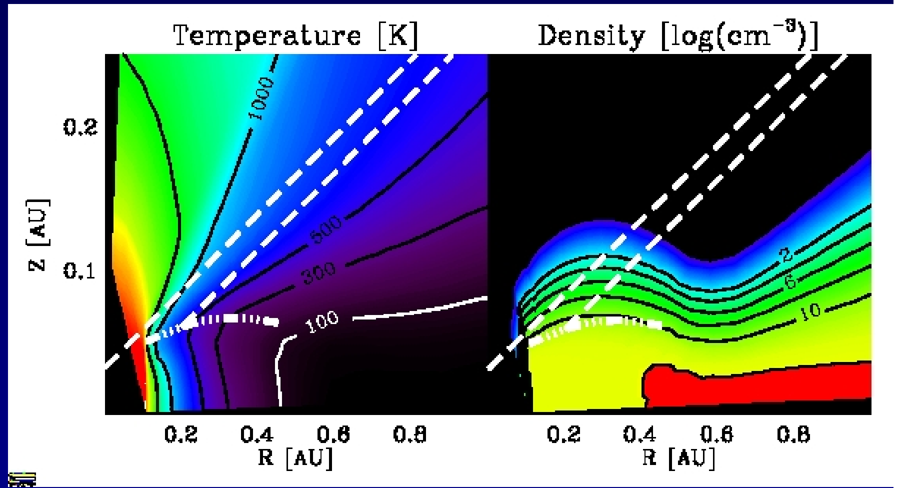
- **Most physical and chemical variations expected to occur on scales of 0.05-0.2'' => *imaging***
  - **Low-mass hot core/disk: 10-100 AU at 300 pc**
  - **High-mass hot core: few hundred AU at 3 kpc**
  - **High-*T* shock zone: 100 AU at 1 kpc**
  - **Dust formation zone: <100 AU at 1 kpc**
- **Improved sensitivity to lines from compact regions**
  - **Abundances down to 10^{-13} w.r.t. H_2**
- **Accurate calibration**
  - **Absolute: 3-5%**
  - **Relative: 1-3%**

ALMA sensitivity: ~1 K rms, 0.25 km/s at 0.2'' in 1 hr at 230-345 GHz

Hot inner disk chemistry

Low-mass: IRS46 in Oph

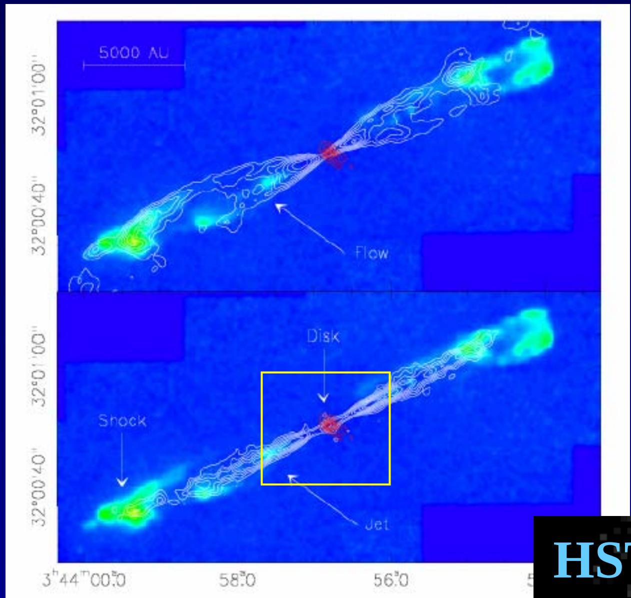




Lahuis et al. 2006

- Surprisingly strong HCN detected by Spitzer at 400 K; mm lines optically thick
- JCMT upper limit => emission from <11 AU radius region
- Can ALMA image these molecules in emisison?

Need for high resolution imaging

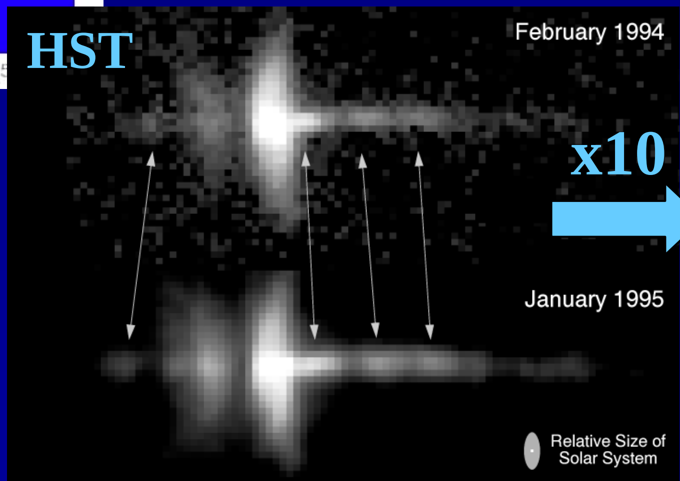


HH211 IRAM

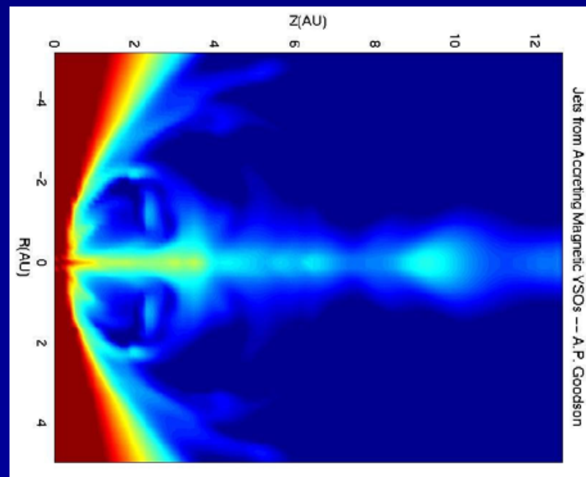
Current mm arrays can only image large scale structures.

ALMA can study the outflows on solar system size scales.

x10

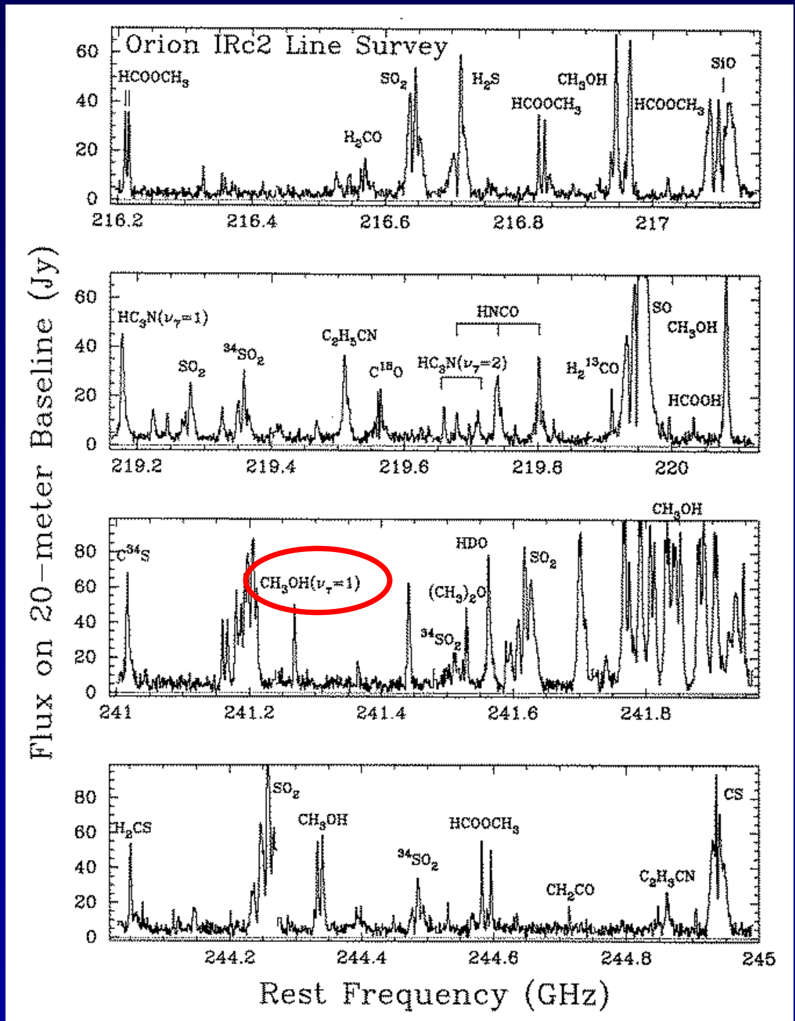


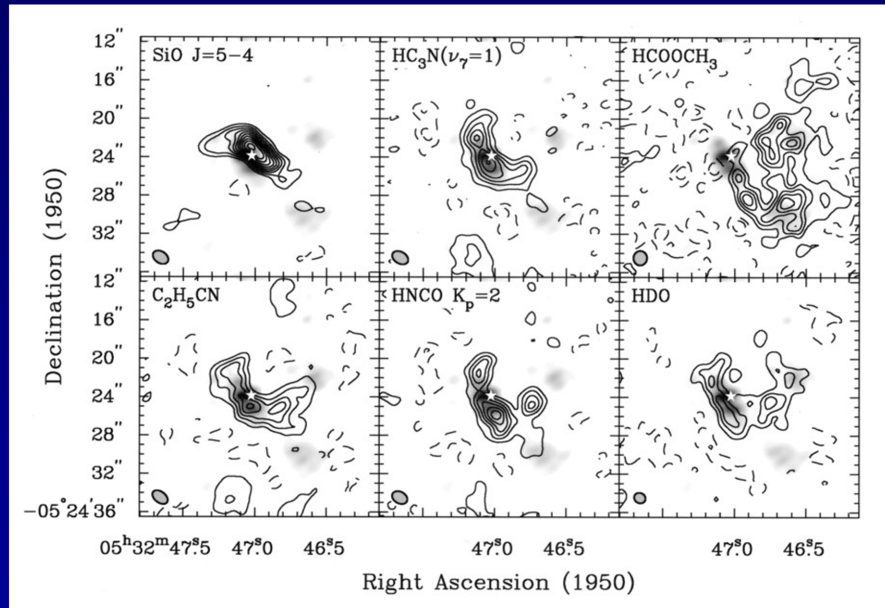
x10



Source: G. Blake

Compact high excitation lines stronger in interferometer





Note strong v=1 CH_3OH lines

Blake et al. 1996

What is needed to make ALMA observations a success

- Good science case
- Laboratory spectra to provide “complete” line catalogs up to 950 GHz
  - Need to have line lists of known species before we can find new complex species
- Theoretical (+laboratory) calculations of collisional rate coefficients over wide range of *T*
- Sophisticated radiative transfer models
- Chemistry codes appropriate for various regions
  - Coupled with dynamics?

ALMA and other facilities

SOFIA 2007?

Various spectro-meters, incl. heterodyne

Herschel 2008
HIFI: heterodyne spectrometer 480- 1250; 1410-1910 GHz

Spectral surveys of ALMA targets!

- Importance of long-wavelength facilties?
- Is ALMA Band 1 enough?