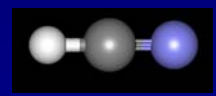
Building complex molecules during star- and planet formation:

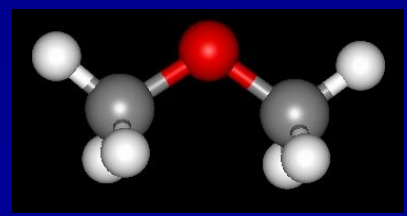
Synergy of infrared and millimeter observations

Examples from low-mass star formation



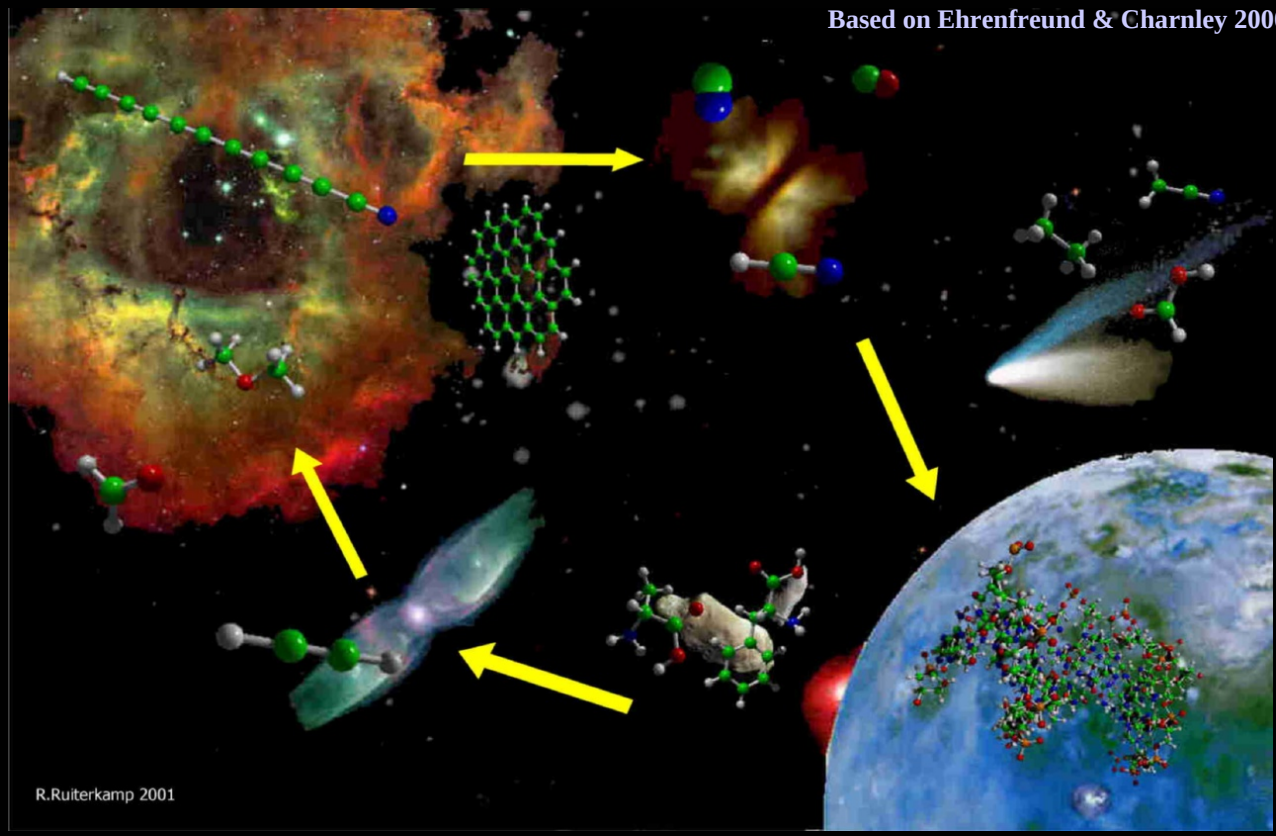
Ewine F. van Dishoeck

Leiden Observatory



Detection of exo-planets:

Renewed interest in lifecycle of gas and dust

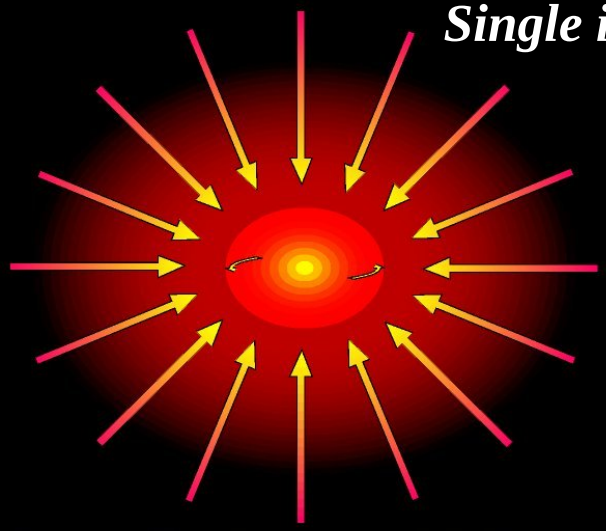


- Inventory of gas + solid at different evolutionary stages?
- How far does chemical complexity go?
- Chemical diagnostics of protostellar evolution?

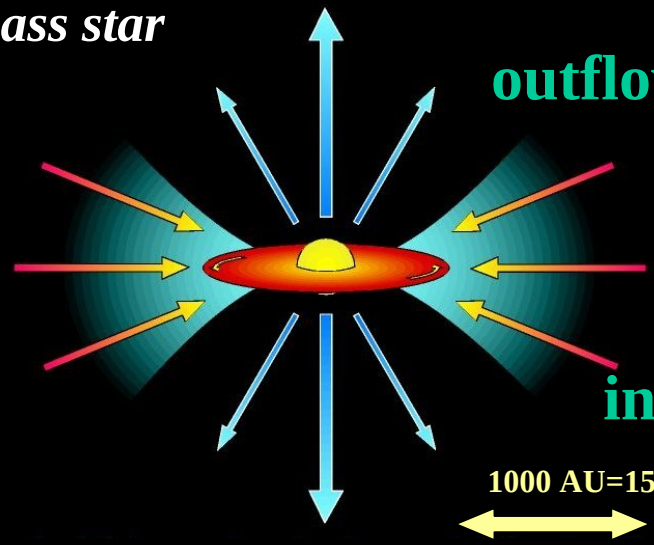
Need high spectral and spatial resolution observations at IR and mm
=> ALMA, Herschel, JWST, ELT

Scenario for star- and planet formation

Single isolated low-mass star

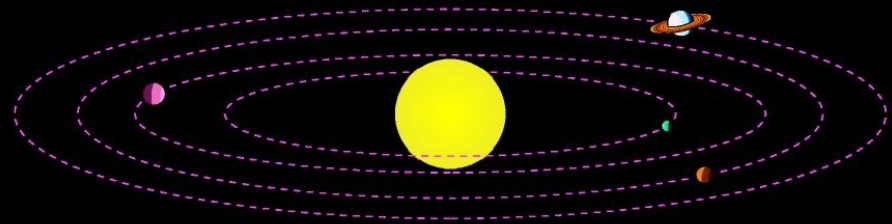


Factor 1000 smaller



Cloud collapse t=0

Protostar with disk t=10^5 yr



Formation planets t=10^6-10^7 yr

Solar system t>10^8 yr

Virtually all current data spatially unresolved

Infrared vs submillimeter

- **Submillimeter:**
  - **Very high spectral resolution ($R>10^6$, <0.1 km/s)**
  - **Many gas-phase molecules with abundances down to 10^{-11} w.r.t. H_2**
  - **Emission => map of region**
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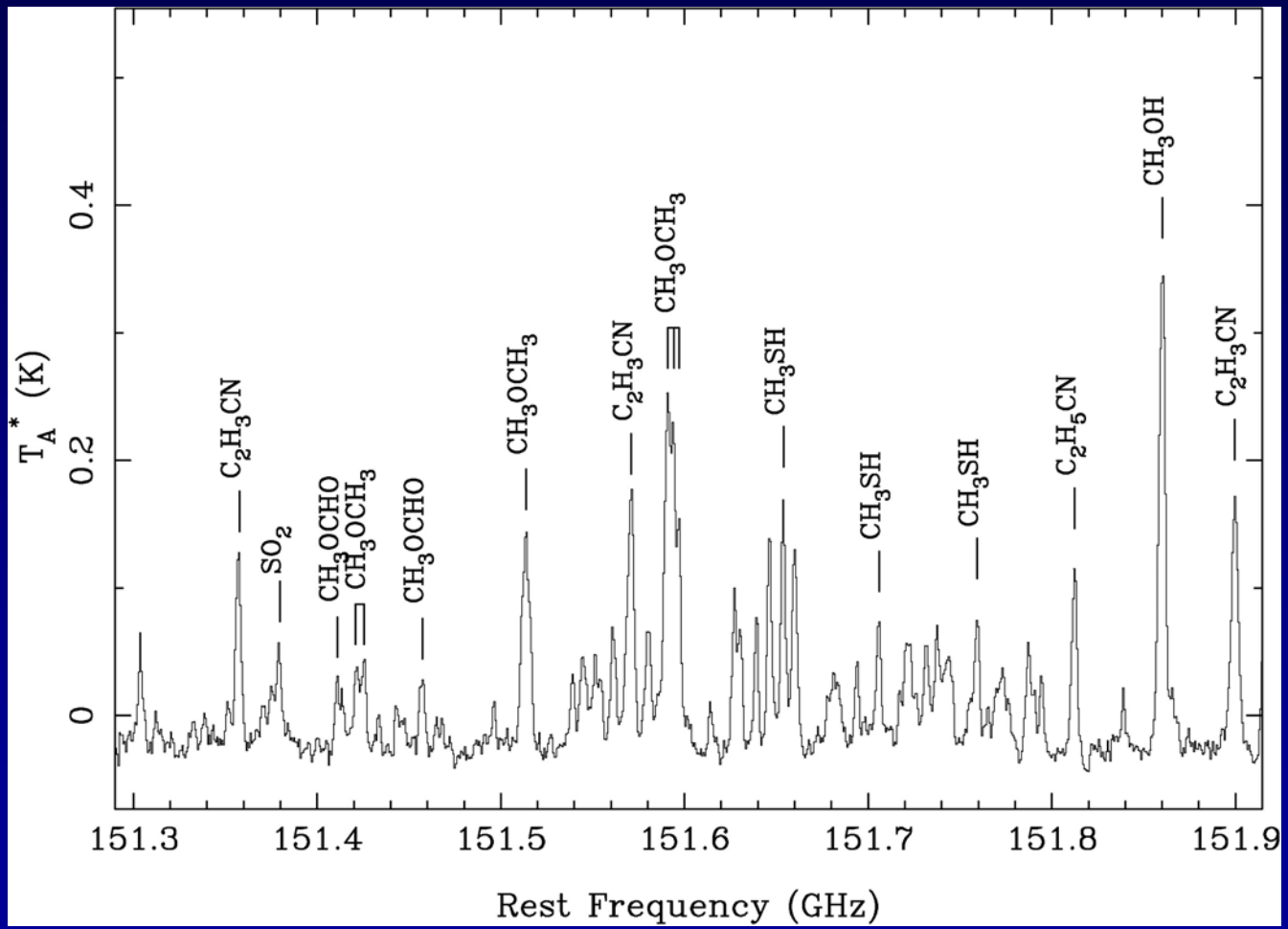
  - **Molecules without permanent dipole moments (H_2, C_2H_2, CH_4, CO_2, CH_3, …)**
  - **Absorption => pencil beam line-of-sight**

Rich (sub)millimeter spectroscopy

Massive protostar

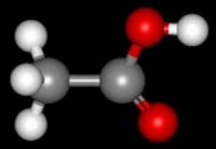


G327.1
SEST

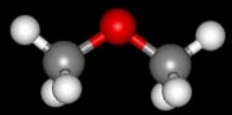
Gibb et al.
2001

Some complex organic molecules

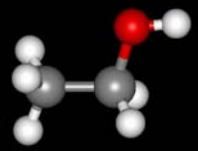
Detected



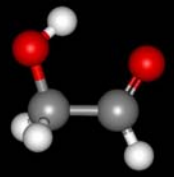
Acetic acid



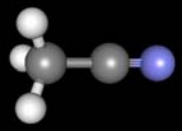
Di-methyl ether



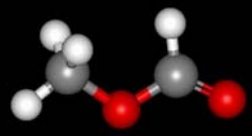
Ethanol



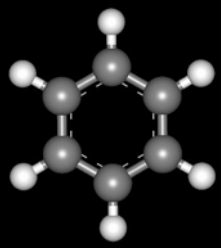
Sugar



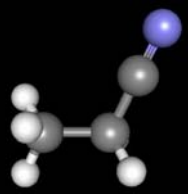
Methyl cyanide



Methyl formate

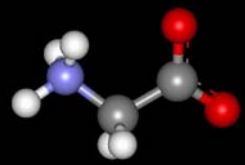


Benzene

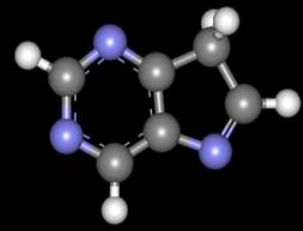


Ethyl cyanide

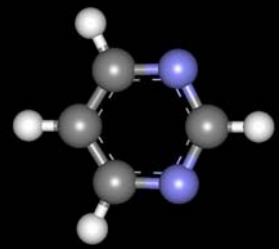
Not (yet) detected



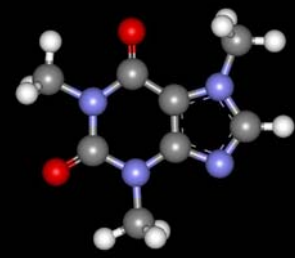
Glycine



Purine



Pyrimidine



Caffeine

Based on Ehrenfreund 2003

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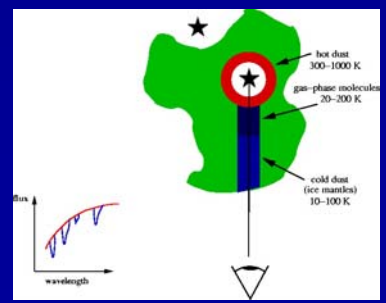
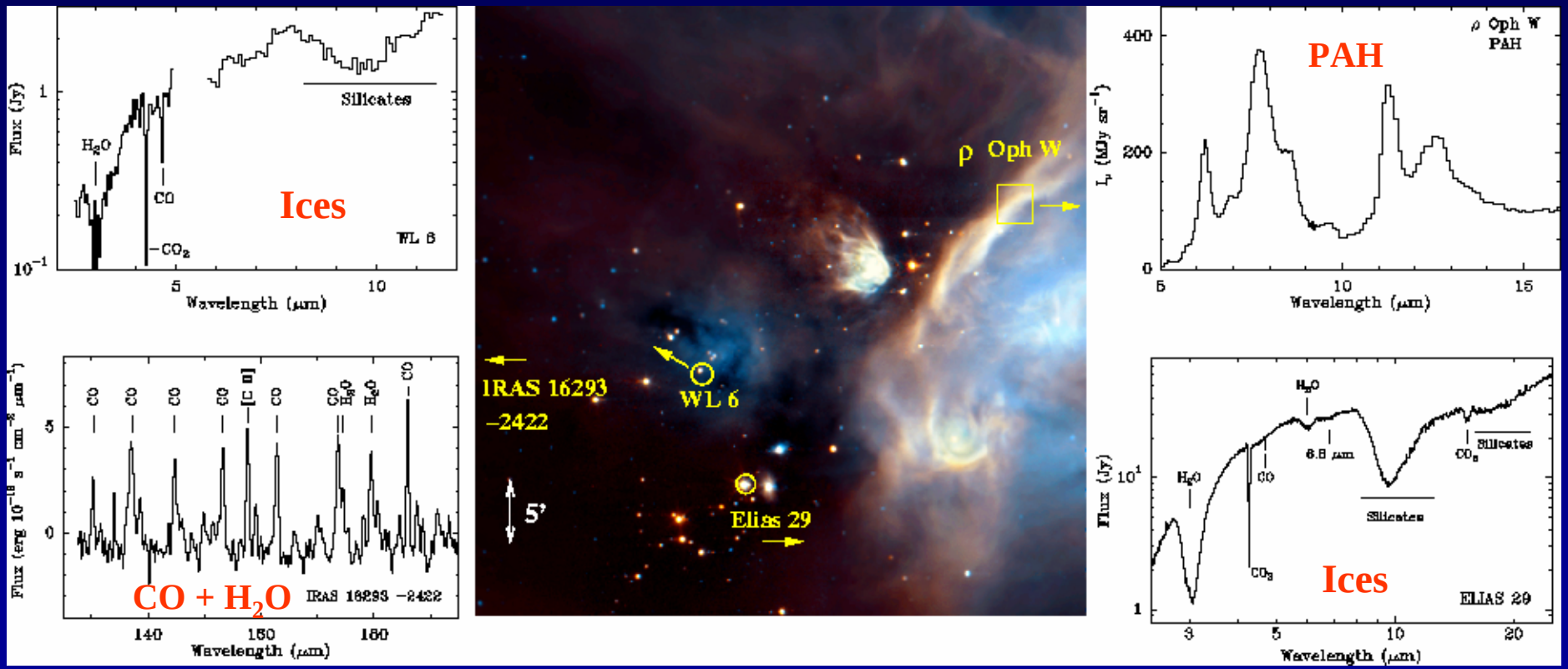
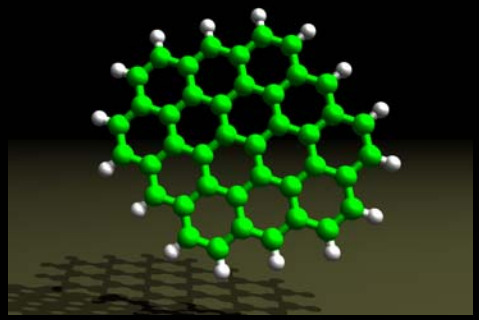


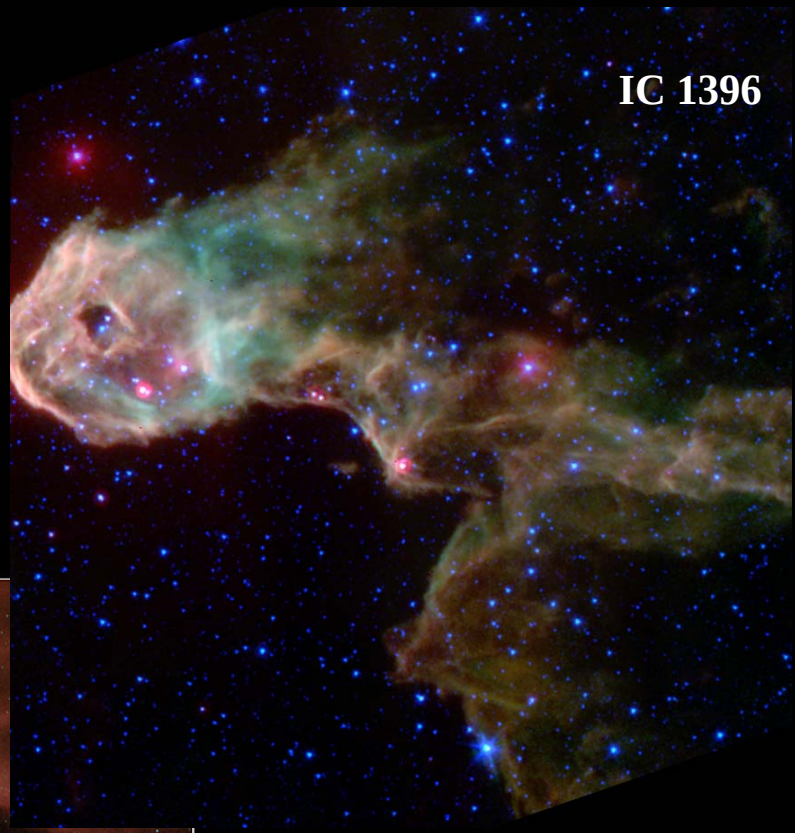
Rich variety in infrared spectroscopy

Examples from ISO



PAHs everywhere





Reach et al. 2004

Melnick et al. 2004

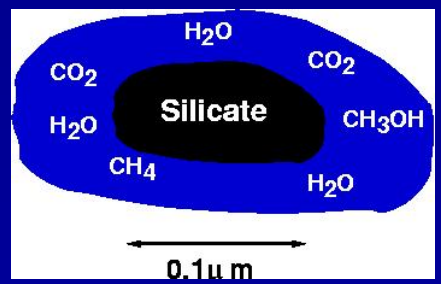
Red = 8 μm emission = PAH

Chemical Scenario

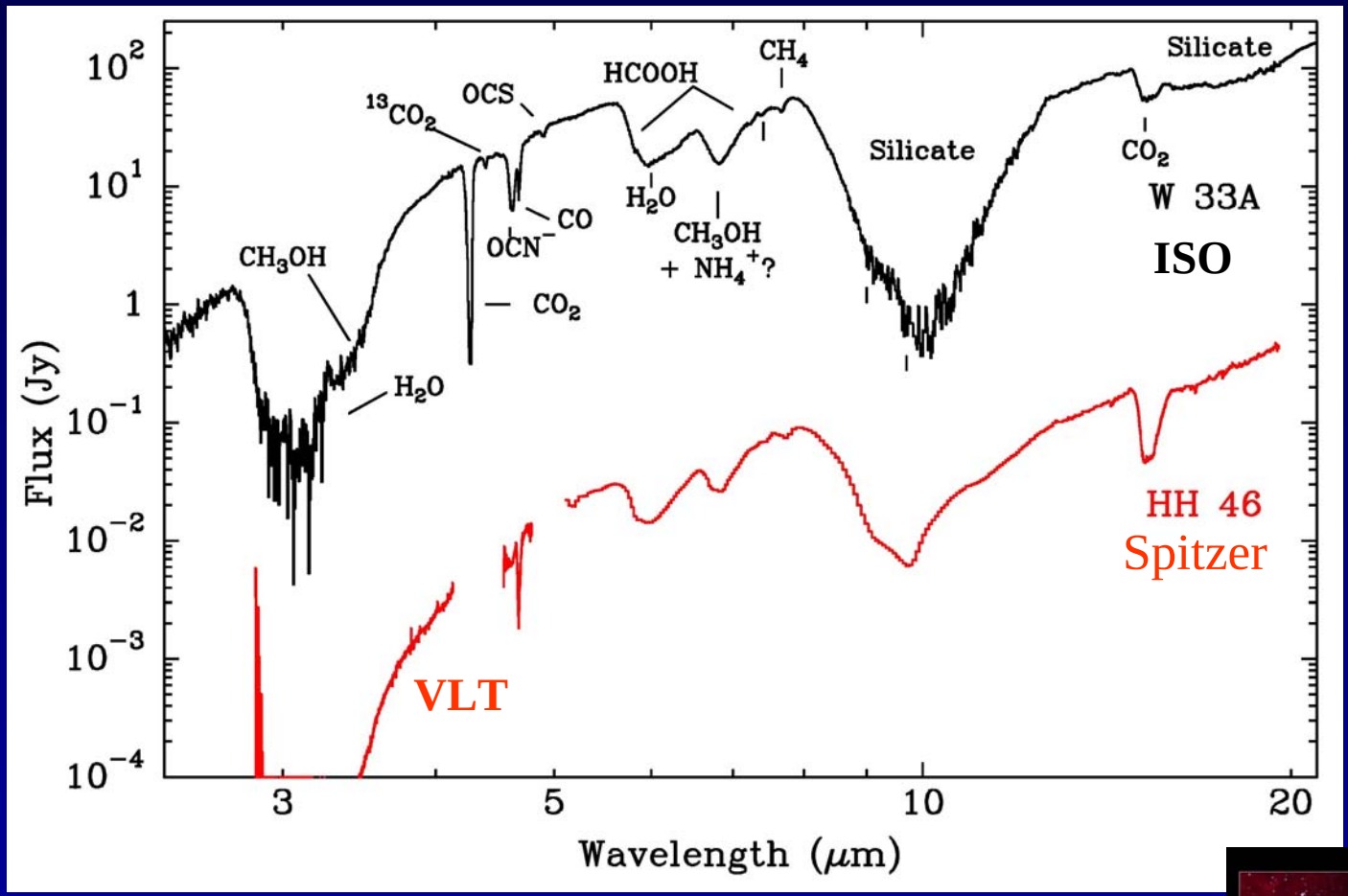
- **Heavy freeze-out of molecules onto grains in cold pre-stellar phase**
- **Grain surface reactions produce new species:**

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

$$CO \xrightarrow{O} CO_2$$



W33A vs HH 46 ices: massive vs low-mass YSO

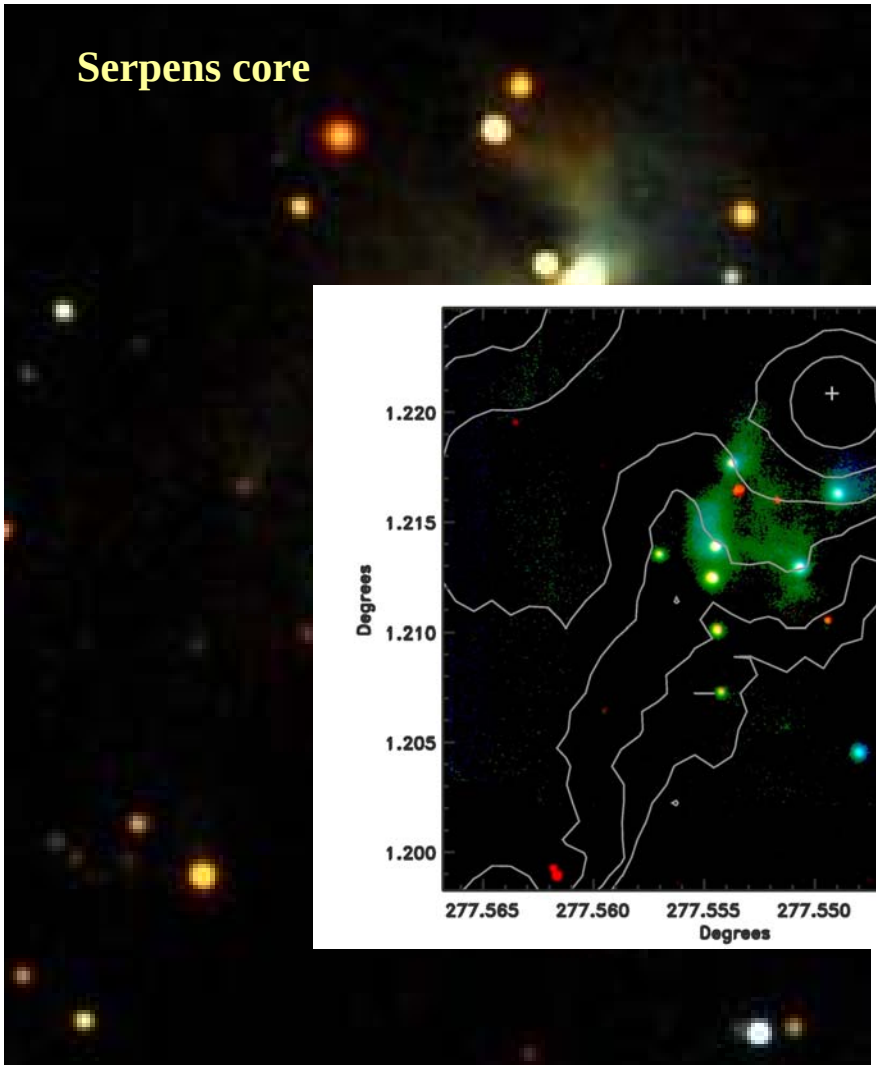


Note similarity in features!

W33A (10^4 L_{sun}): Gibb et al. 2000
HH46 (10 L_{sun}): Noriega-Crespo et al. 2004, Boogert et al. 2004

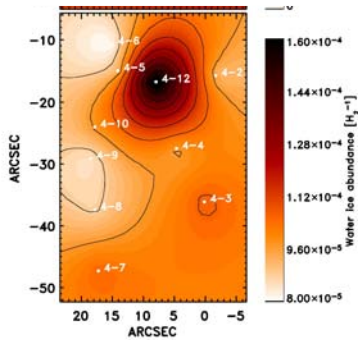
First ice map on 1000 AU scales

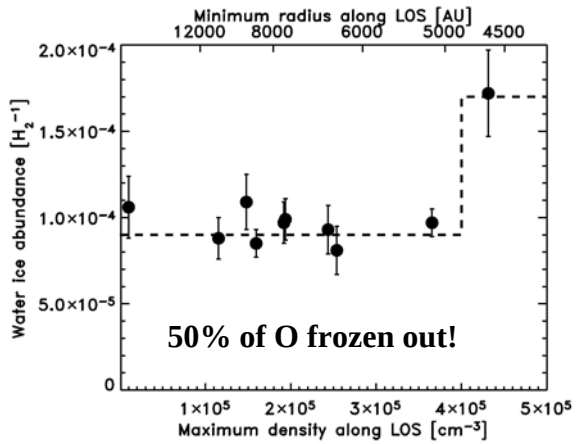
VLT-ISAAC



2Mass

H_2O ice map

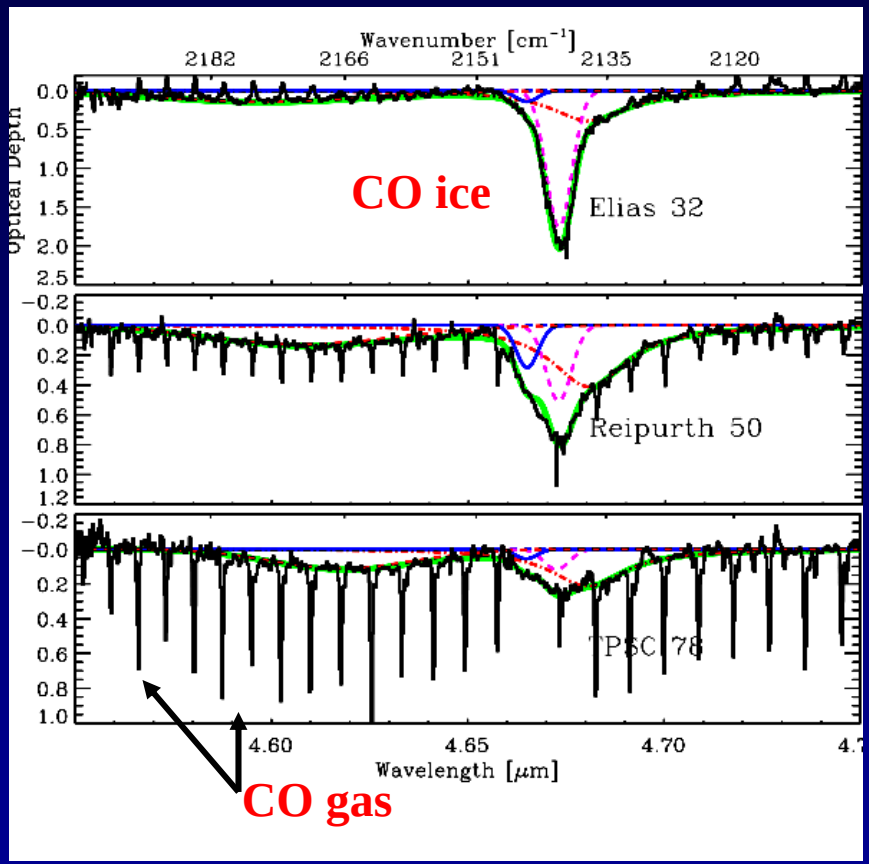




Need next generation IR facilities to make large scale ice maps with resolution comparable to mm maps

Pontoppidan et al. 2004

Ice evaporation low-mass YSO's



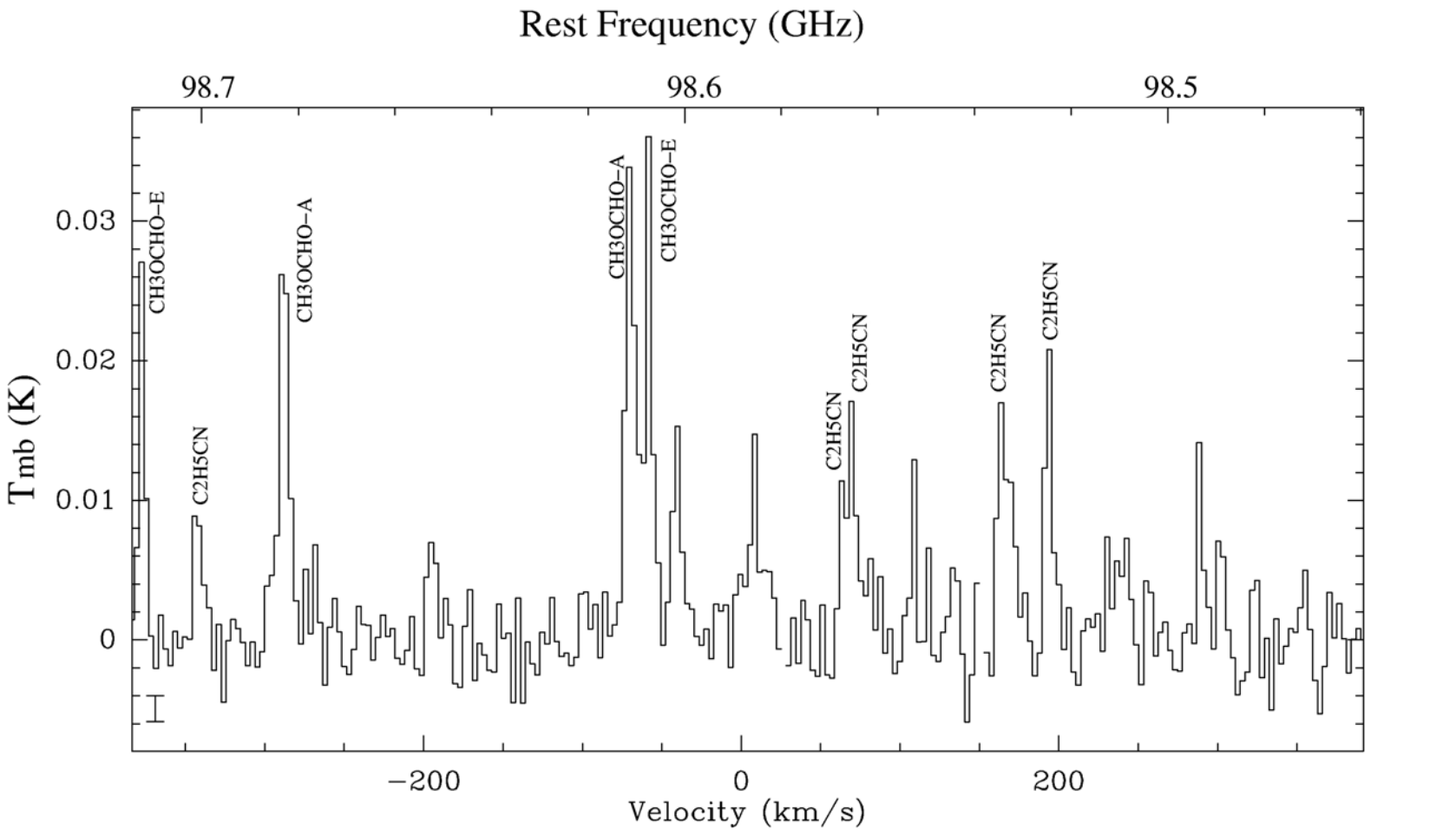
VLT-ISAAC
R=10,000

Previous generation: high-mass YSO's
Spitzer/8-m ground: solar mass YSO's, low to medium resolution
JWST/ELT: subsolar mass, more deeply embedded, high (10^5) spectral res

Pontoppidan et al 2003

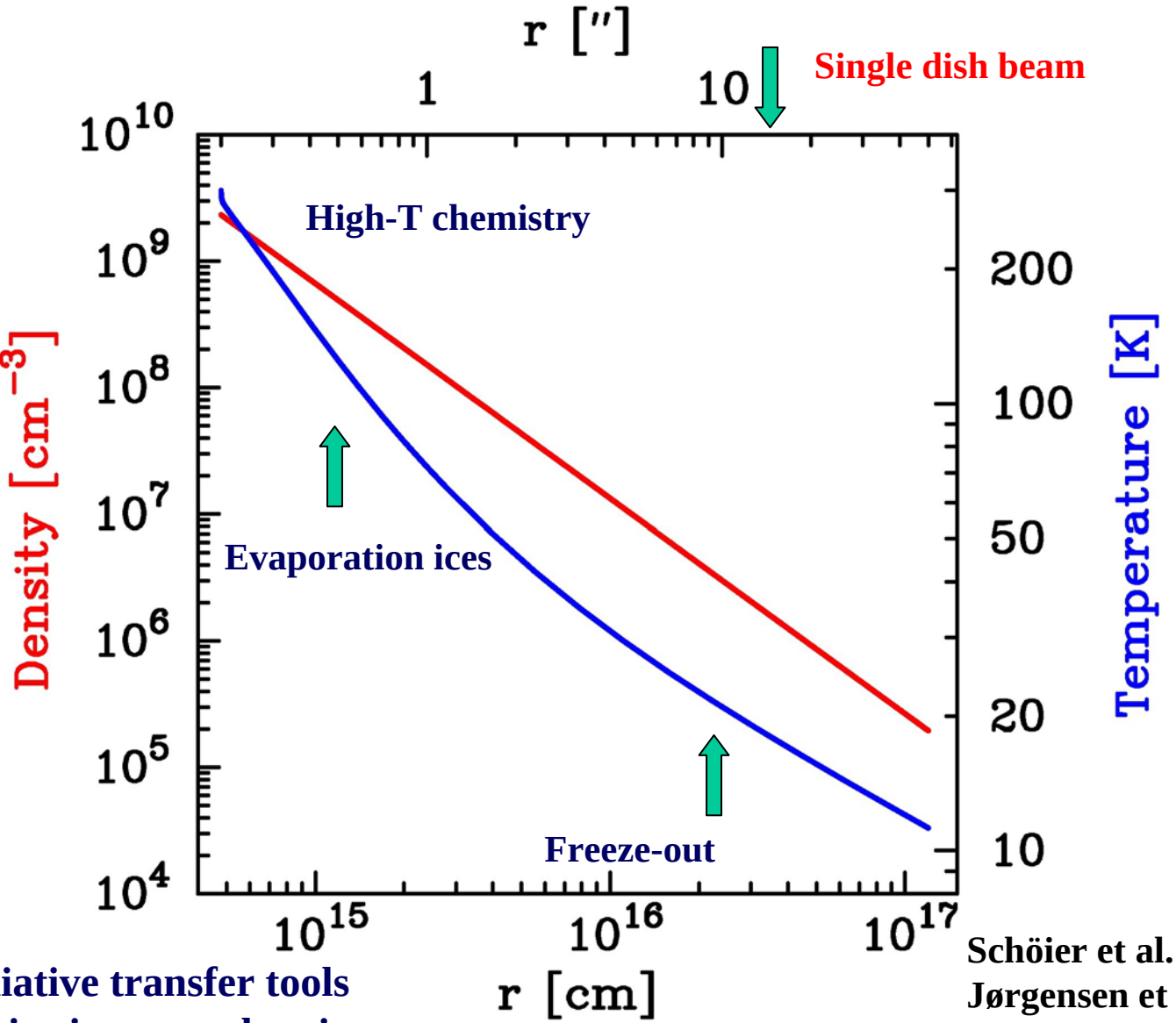
Evaporated ices also seen at mm wavelengths:

Complex organics around the solar-mass star IRAS 16293-2422



vD et al. 1995, Ceccarelli et al. 2000 **IRAM 30m** Cazaux et al. 2003

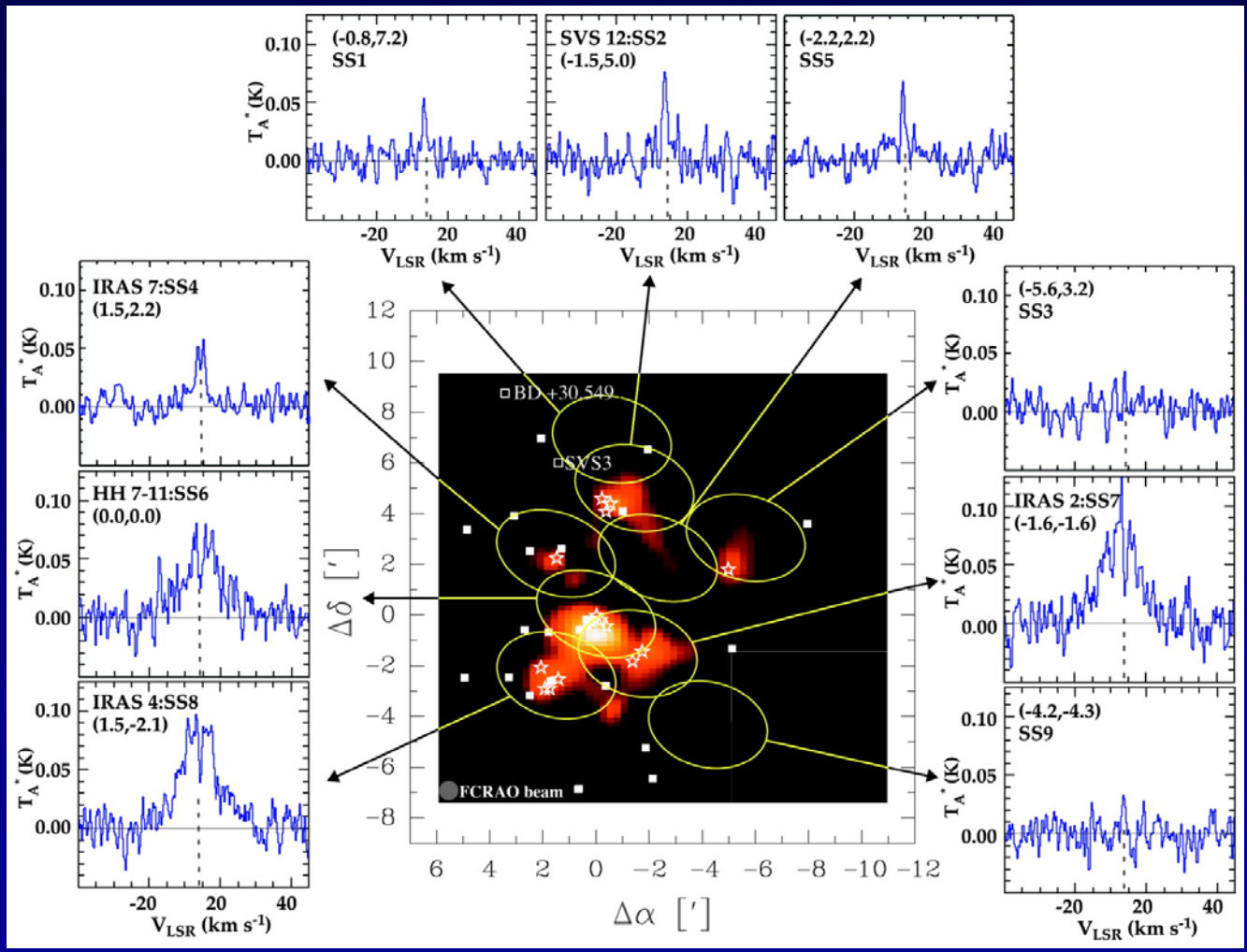
Physical structure protostellar envelope



Schöier et al. 2002
Jørgensen et al. 2002

Development radiative transfer tools
=> Toward quantitative astrochemistry

Gas-phase H_2O map of low-mass star-forming region



Herschel-HIFI can survey H_2O at factor 10 better spatial resolution and sensitivity

Bergin et al. 2003

Chemical Scenario

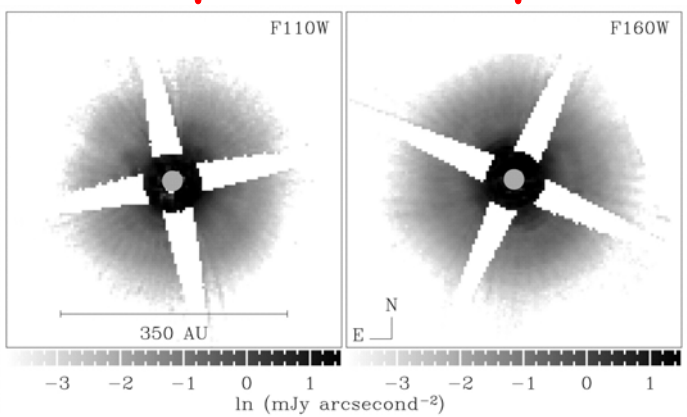
- **Heavy freeze-out of molecules onto grains in cold pre-stellar phase**
- **Grain surface reactions produce new species**
- **Protostar heats surroundings**
- **Fraction of ices and gas ends up in disks; remainder is dispersed**

Disks are small (few arcsec) and contain much less mass than envelope => need next generation telescopes!

Detection of DCO^+ in a circumstellar disk

TW Hya face-on disk

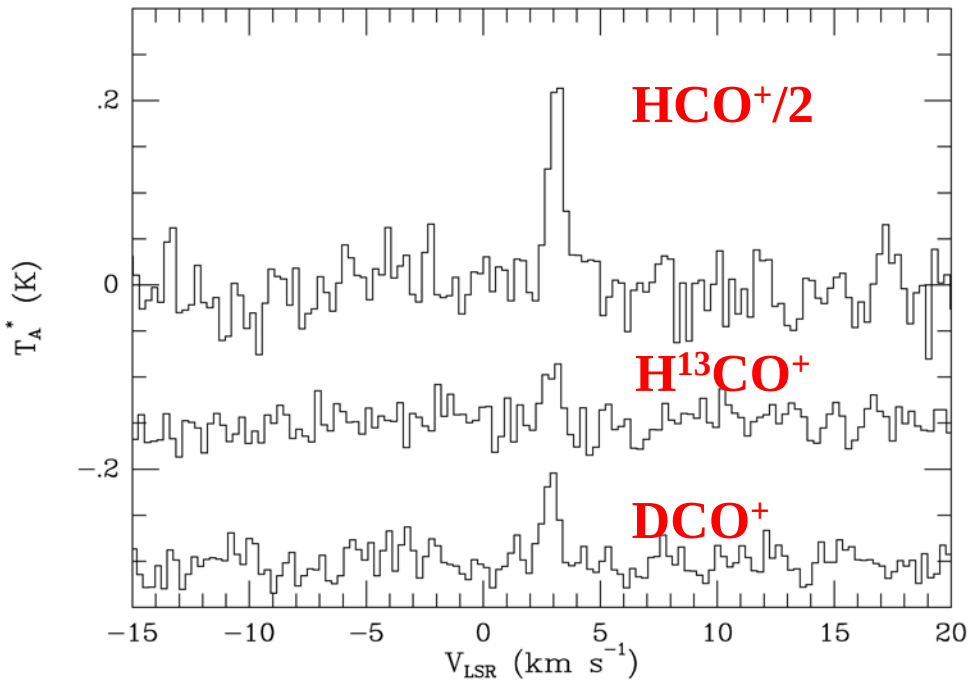
1.1 μm **1.6 μm**



Scattered light => radius 200 AU

Weinberger et al. 2002

JCMT

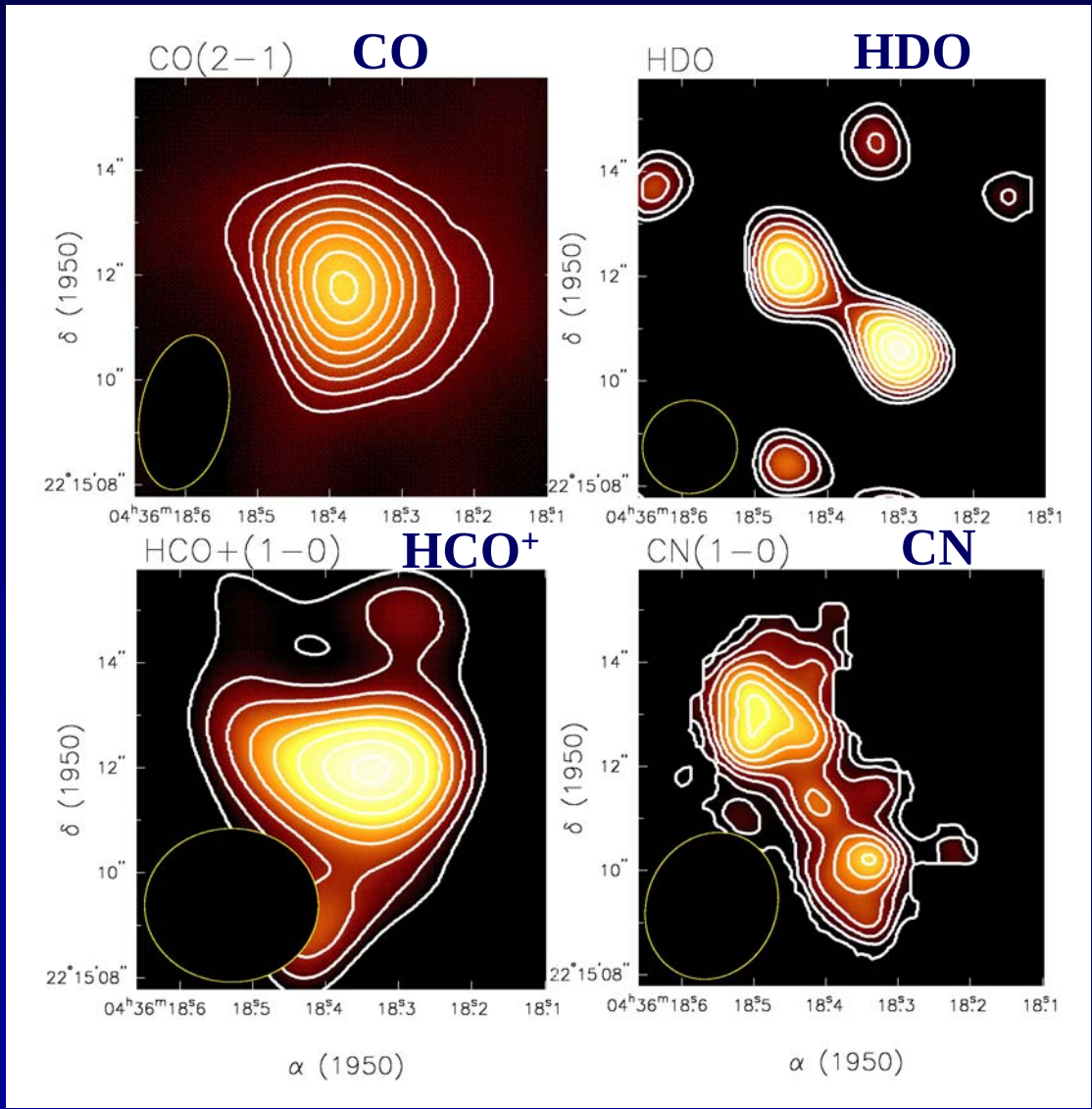


- DCO^+/HCO^+=0.035 => gas in disks is cold with heavy depletions
- Ionization degree sufficient for MRI to operate

Kastner et al. 1997
Dutrey et al. 1997

van Dishoeck et al. 2003

Starting to image the chemistry in disks



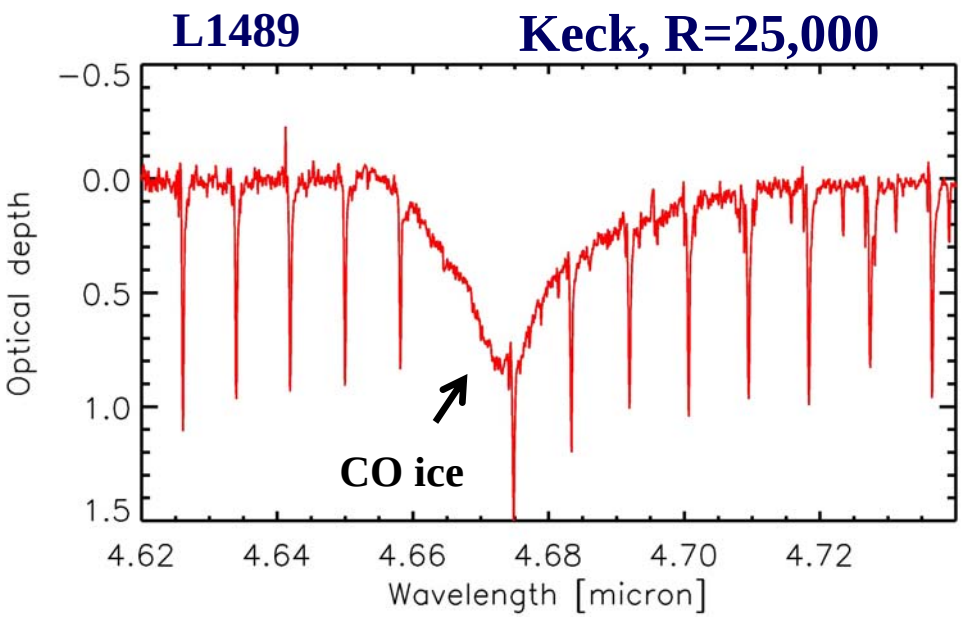
LkCa15

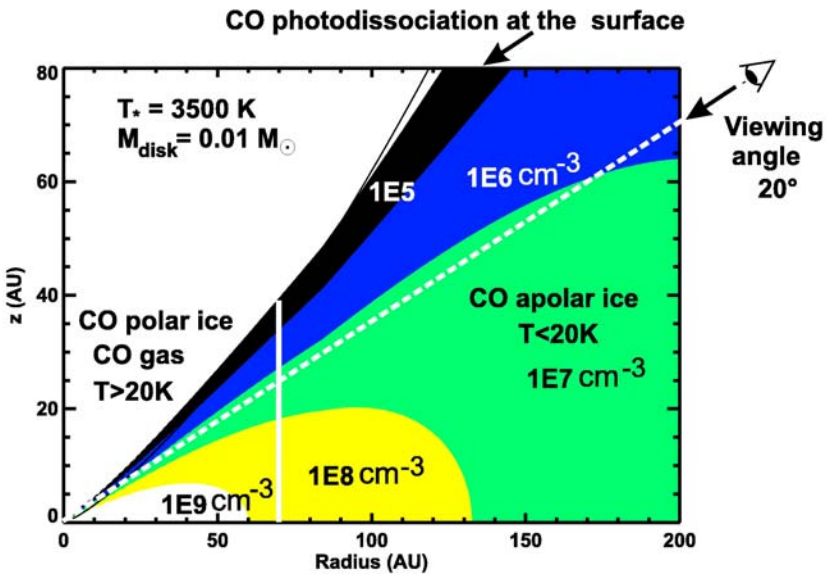
OVRO mm array

Aikawa et al. 2003

Kessler, Qi, Blake et al. 2003

Solid and gaseous CO toward a young, large edge-on disk



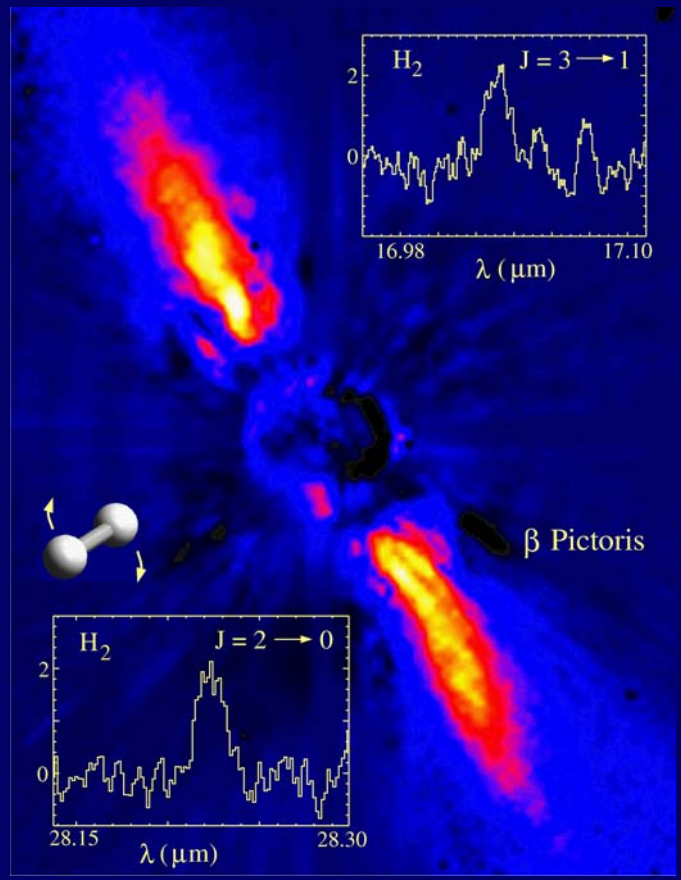


- Red wing line profiles traces accretion to within 0.1 AU from star
- Warm CO gas (up to 200 K), with CO_{gas}/CO_{solid}~10

Need JWST, ELT to survey large number of edge-on disks

Boogert, Hogerheijde & Blake 2002

Transitional disks: dust and gas



When does gas disappear from disk? => timescale Jovian planet formation
CO not a good tracer due to freeze-out and photodissociation
=> observe H_2 directly

Need high mid-IR spectral resolution to detect weak H_2 lines on continuum

Thi et al. 2001

Summary

- **Mm and IR are both needed to study evolution of gases and solids during star- and planet formation**
- **High spatial and spectral resolution essential => ALMA, JWST, Herschel, ELTs (need high spectral resolution!), future far-infrared space mission?**
- **Complex organic molecules are detected both in gases and solids in protostellar regions; are they present in disks?**