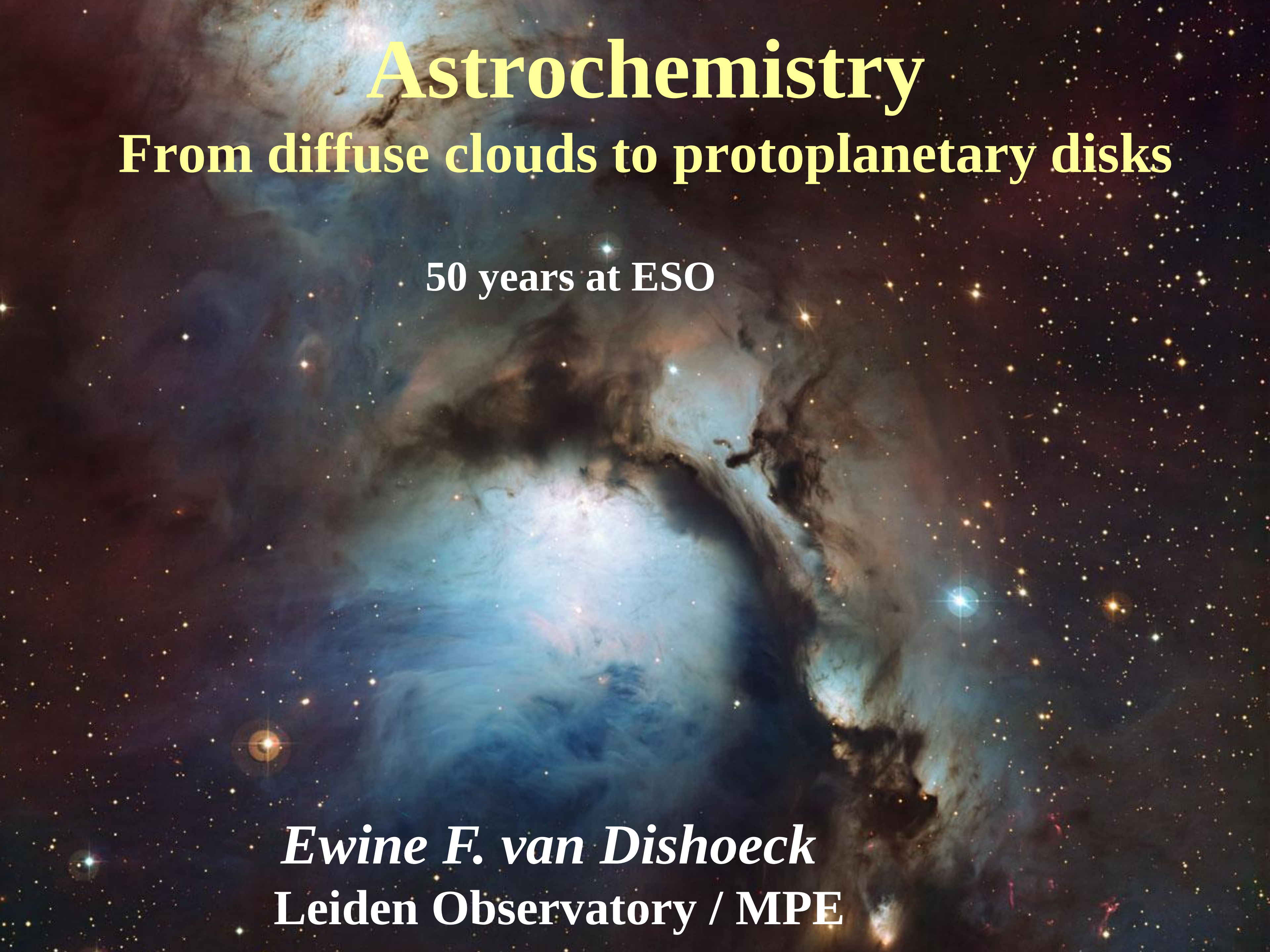


Astrochemistry

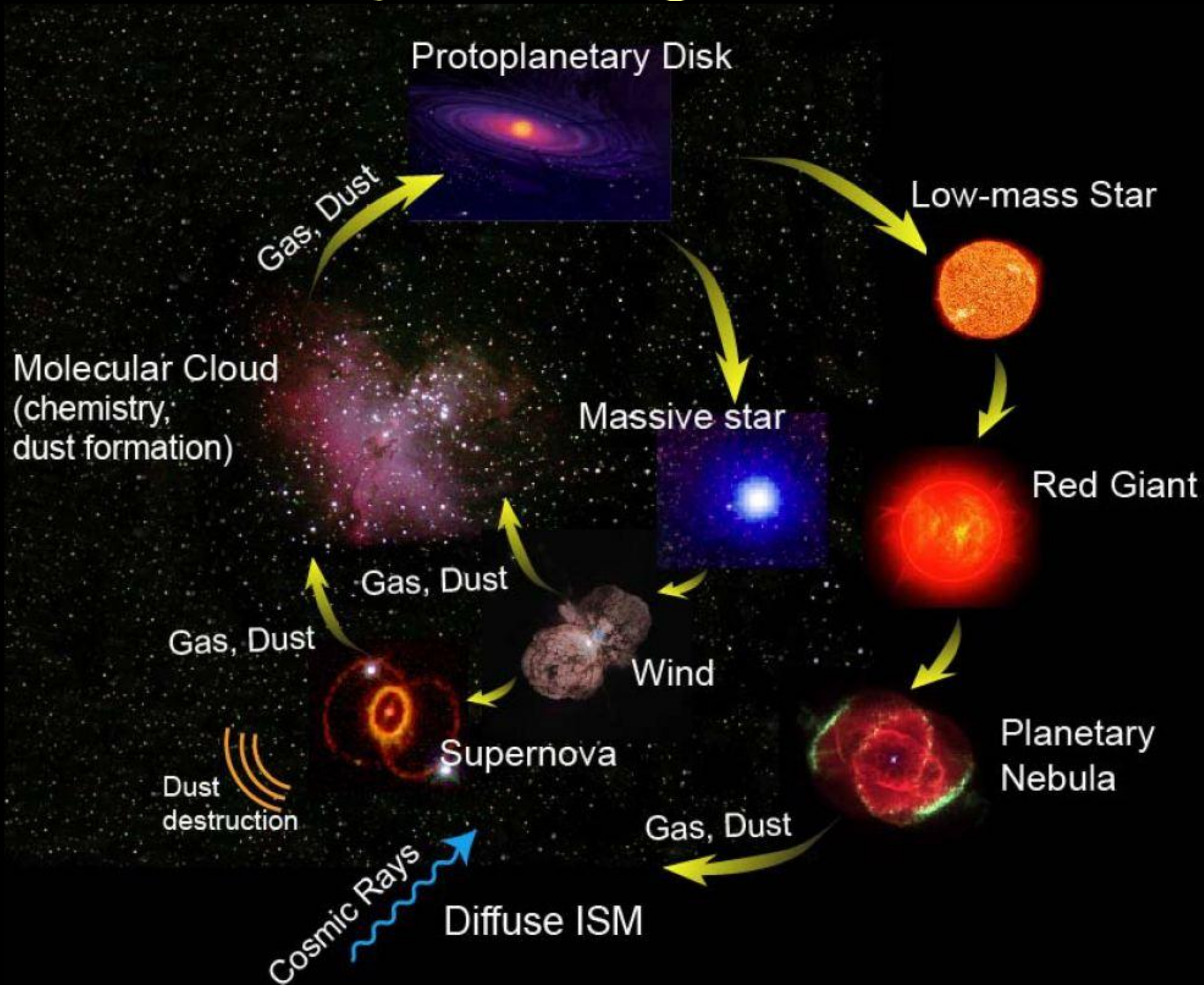
From diffuse clouds to protoplanetary disks

50 years at ESO

Ewine F. van Dishoeck

Leiden Observatory / MPE

Life cycle of gas and dust



Outline

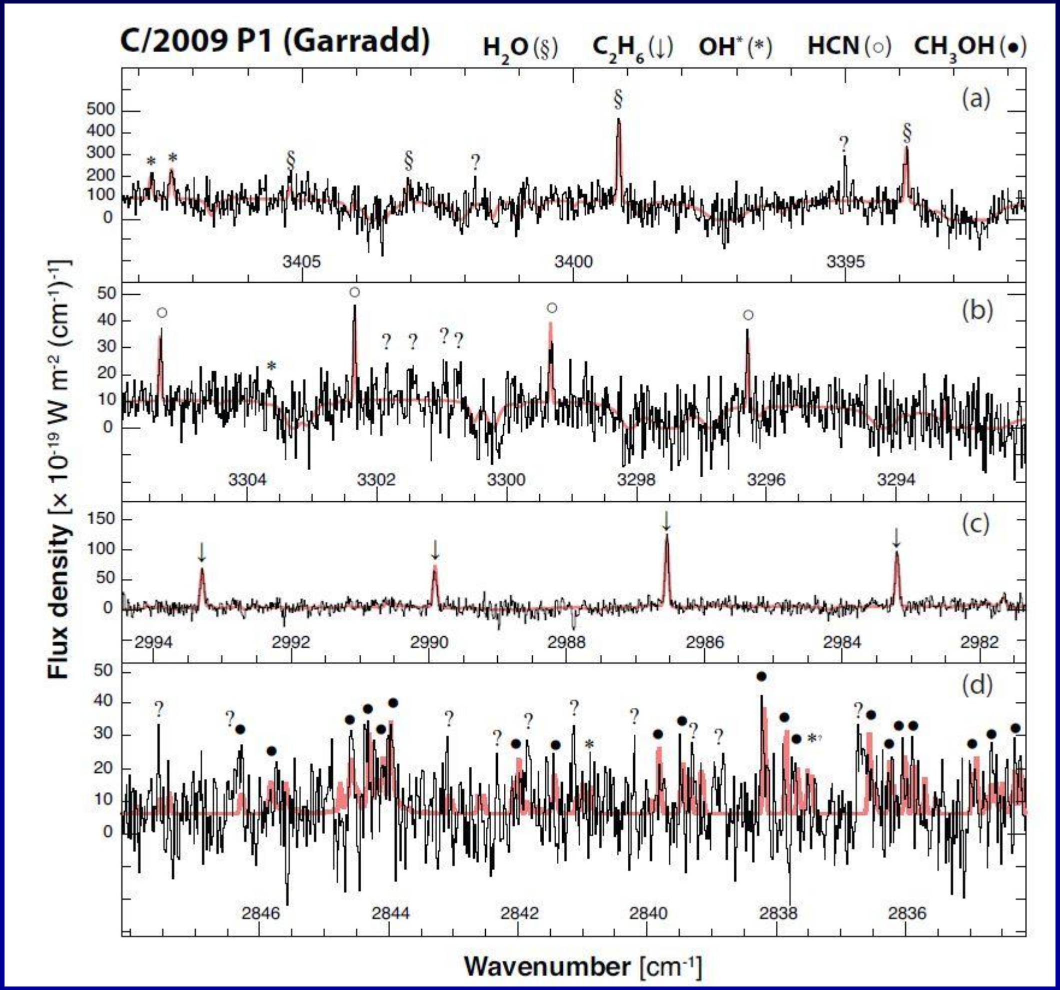
- Introduction
- Diffuse and translucent clouds
- Dense molecular clouds, LMC/SMC
- Star-forming regions
- Protoplanetary disks

There is no such thing as too high spectral resolution
(J.H. Black)

First opportunity for astrochemistry at ESO

Comet coma contains many molecules but no record of published ESO spectra

Now: parent molecules detected with exquisite sensitivity



- Make link between Solar system and ISM material

Paganini +12

VLT-CRIRES
ESO frontrunner!

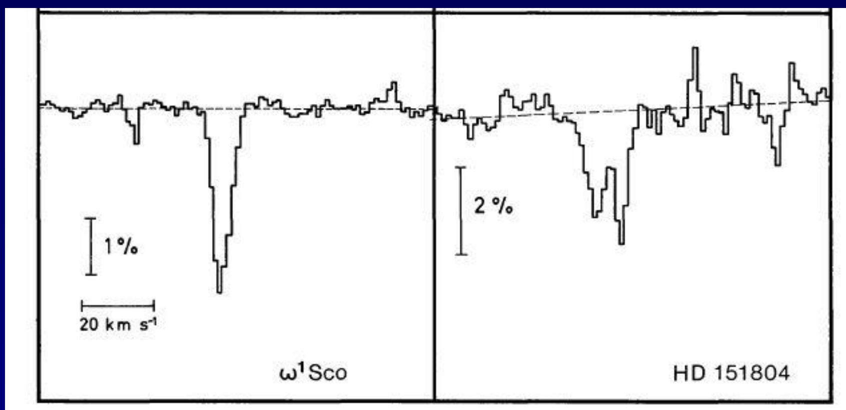
Diffuse and translucent clouds

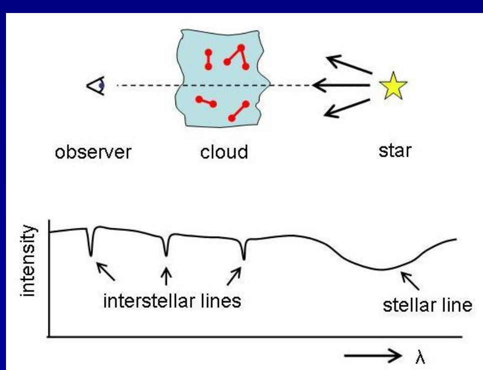
- Availability of high resolution (R~80000) optical spectrometer on 1.5m CAT in 1982
- High dynamic range
- Well suited for ISM studies

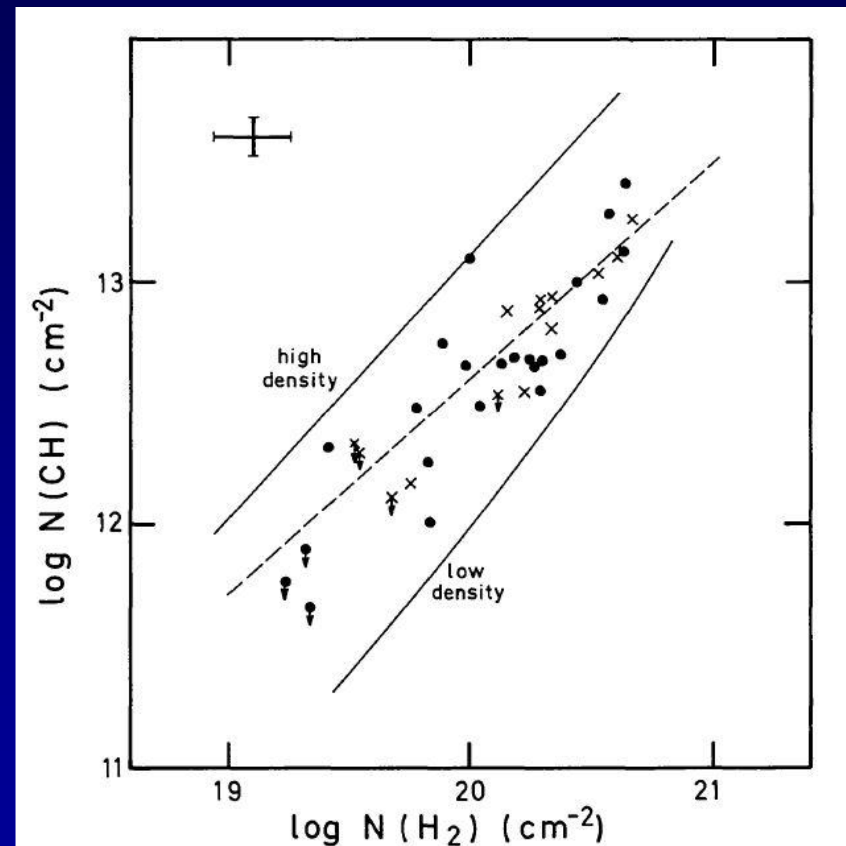
Coude Echelle Spectrometer Enard 1979

Interstellar CH as tracer of H_2

CH 4300 Å



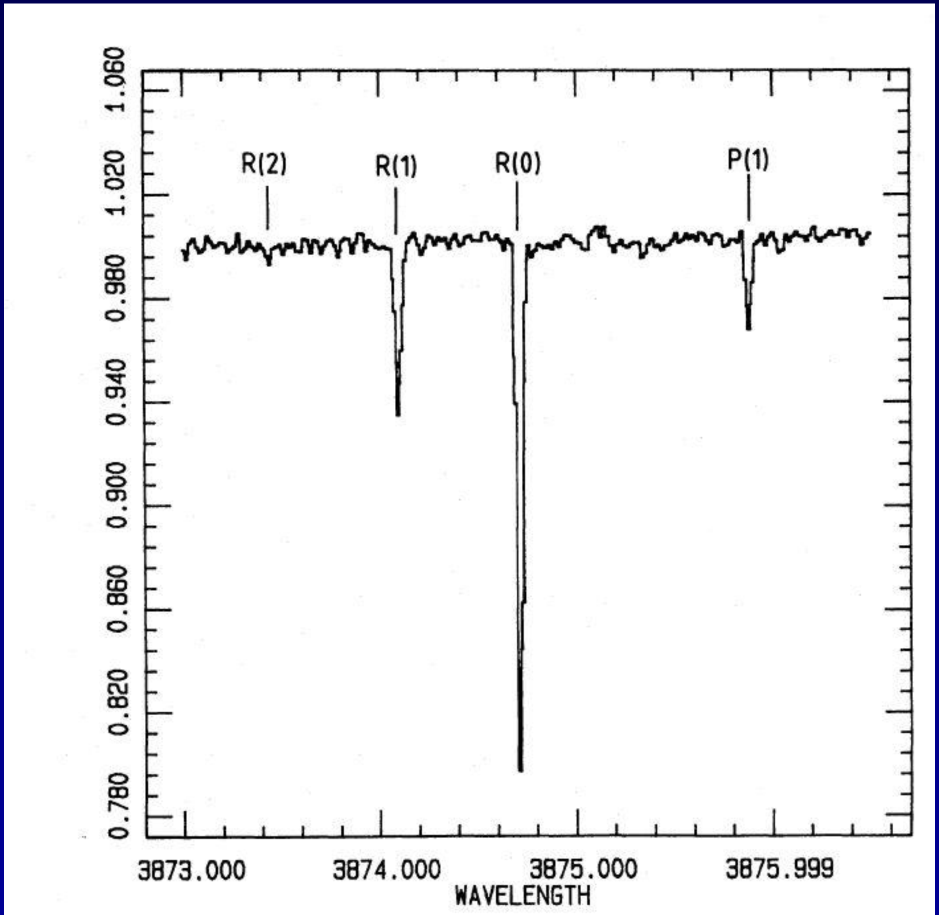




Danks+84
Gredel 97

Tests of simple gas-phase chemistry

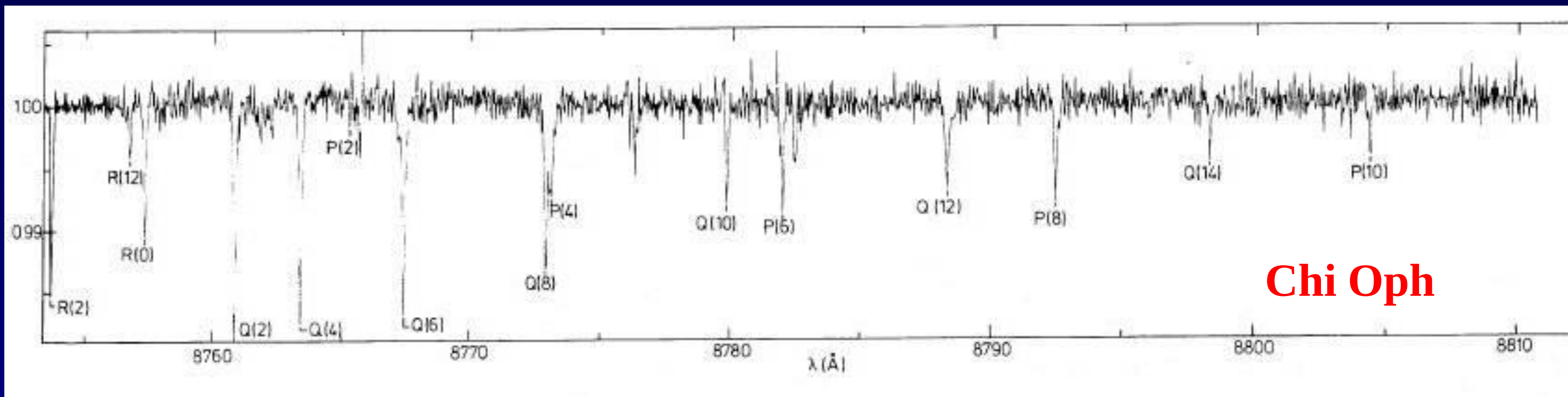
CMB temperature from CN



Crane+86

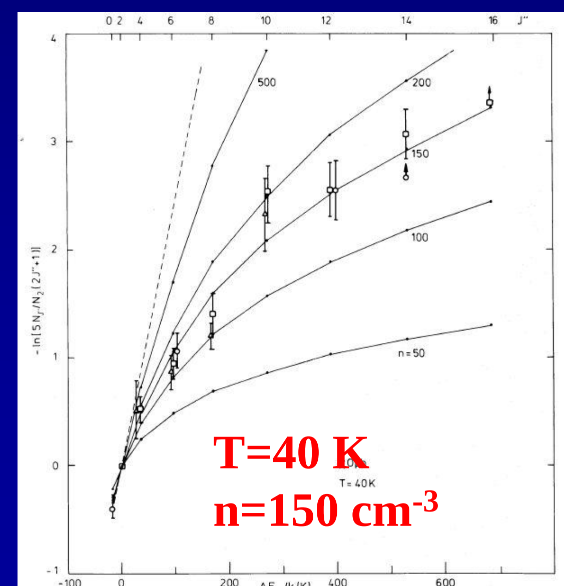
$T_{ex}=T_{CMB}=2.74\pm0.05$ K

Interstellar C_2: measure *T*, *n*



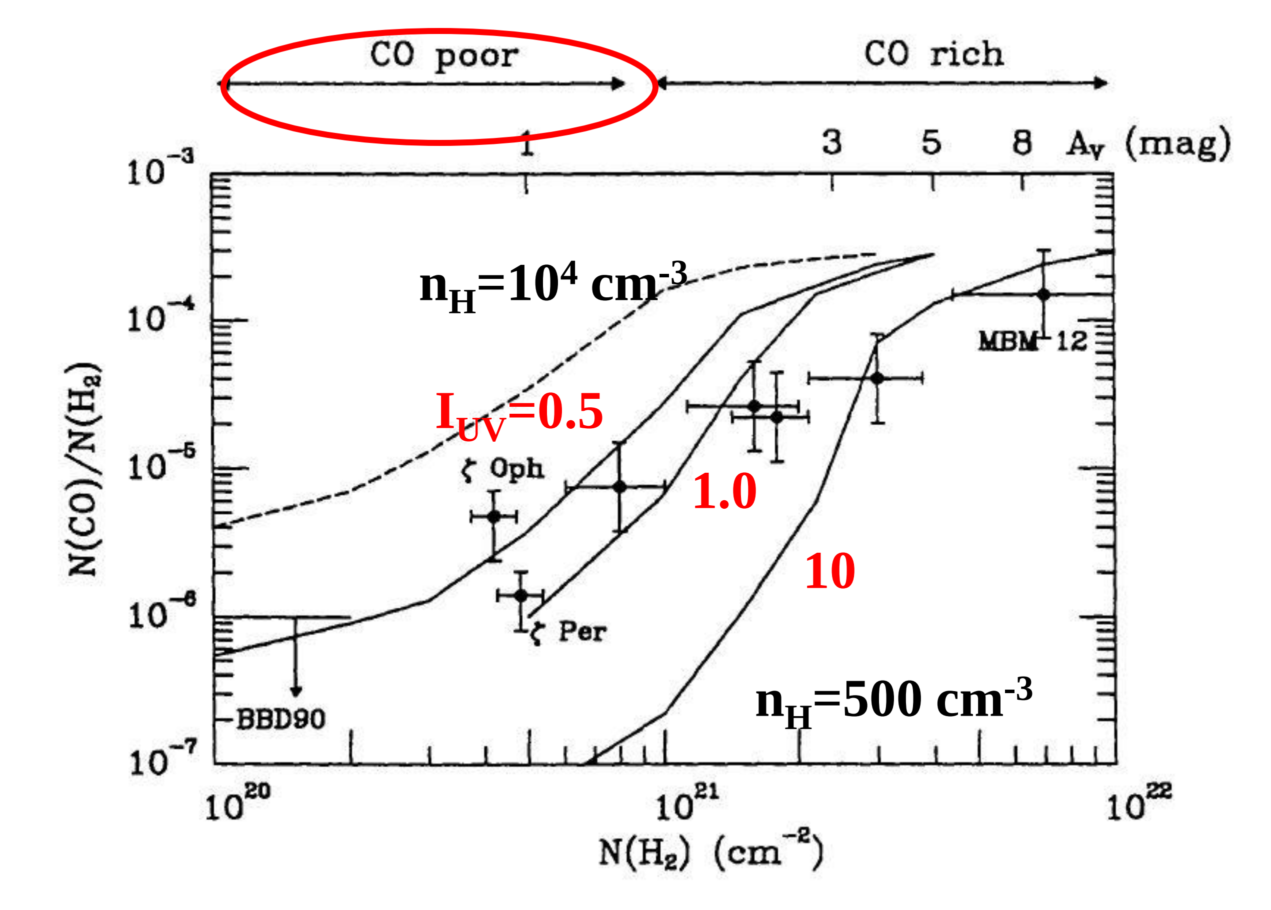
Observations of interstellar C_2 toward χ Oph, HD 154368, 147889 and 149404★

Ewine F. van Dishoeck and Tim de Zeeuw *Sterrewacht Leiden, PO Box 9513, 2300 RA Leiden, The Netherlands* **1983**



vD & Black 1982, 1989

Full characterization of translucent clouds (A_V~1-5 mag)



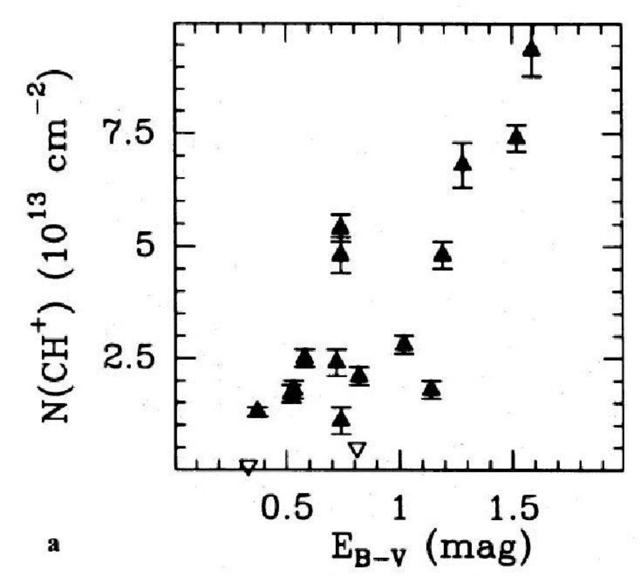
Not all carbon converted yet into CO at lowA_v

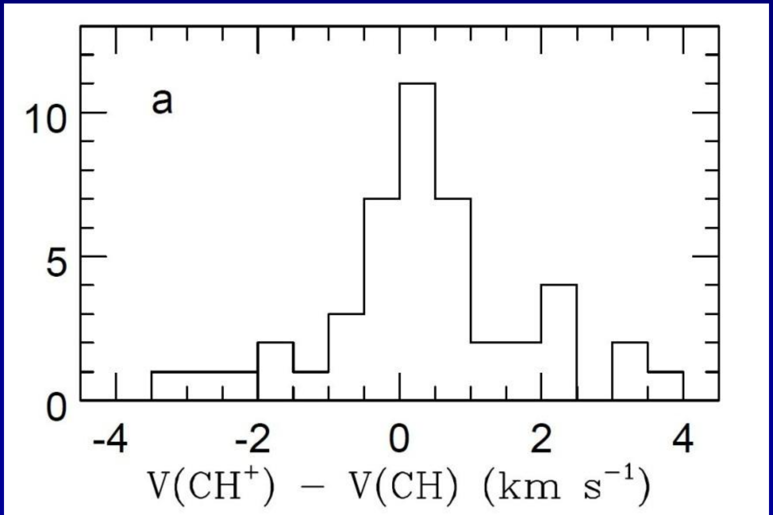
vD&Black 88, 89
vD 92

These clouds now known as the 'dark gas' (Grenier+05)
Used to be known as: 'CO poor gas'

The CH^+ mystery

- CH^+ correlated with excited H_2 J=3-5
- CH^+ not significantly shifted from CH
- CH^+ increases with extinction

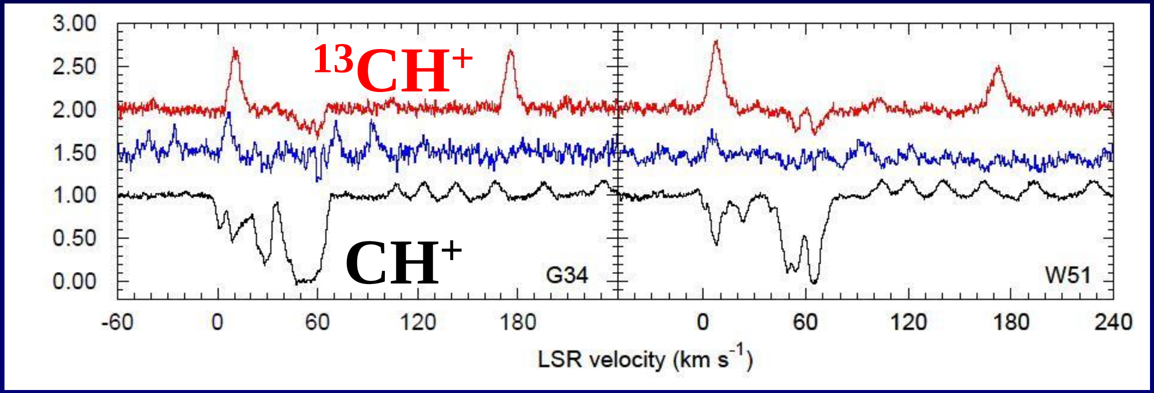




Lambert & Danks 86, Gredel+93, Gredel 97

Origin in weak shocks associated with turbulence ?

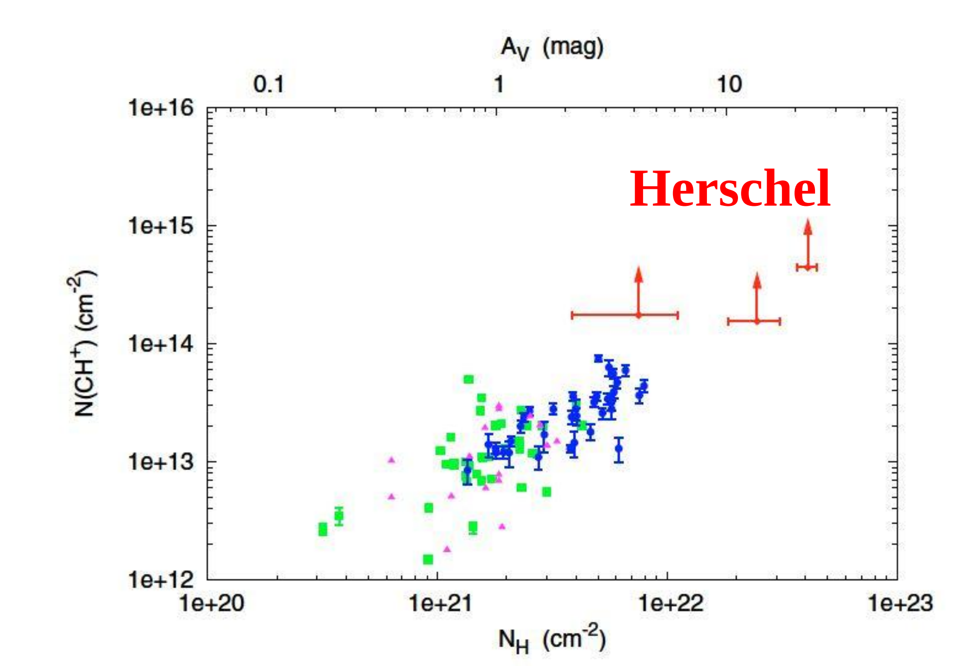
Herschel extends to high A_V



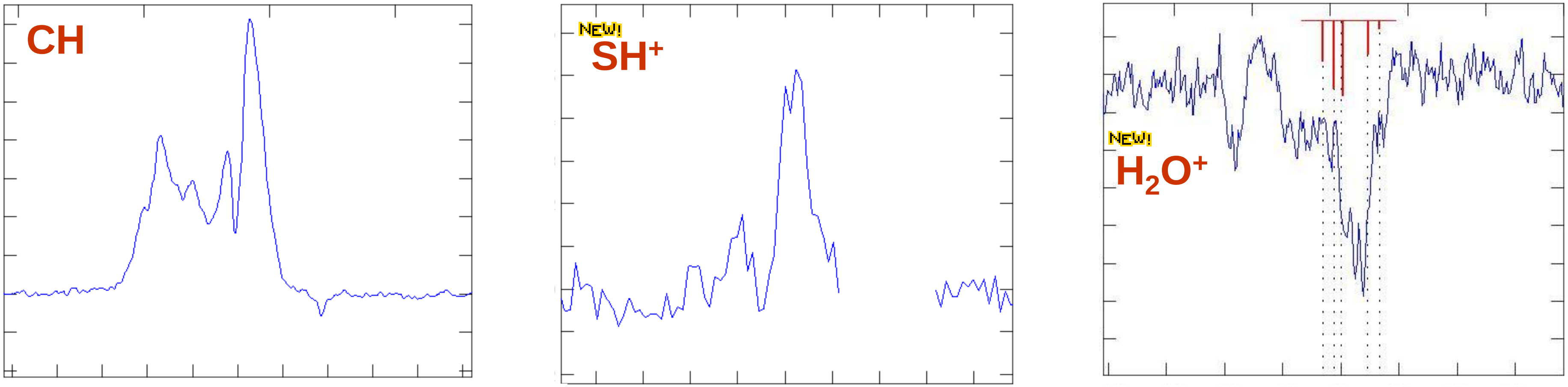
Herschel spectra

Development of 'Turbulence Driven Regions' (TDRs) and their chemistry

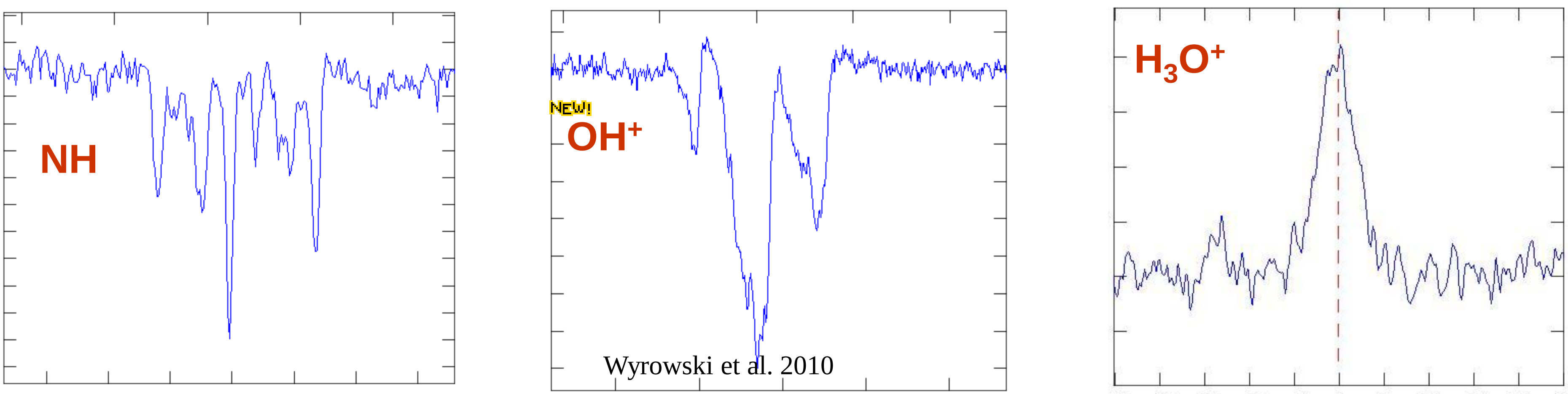
Falgarone+ 10
Godard+ 12



Simple hydrides observed with APEX and Herschel



Menten et al. 2010

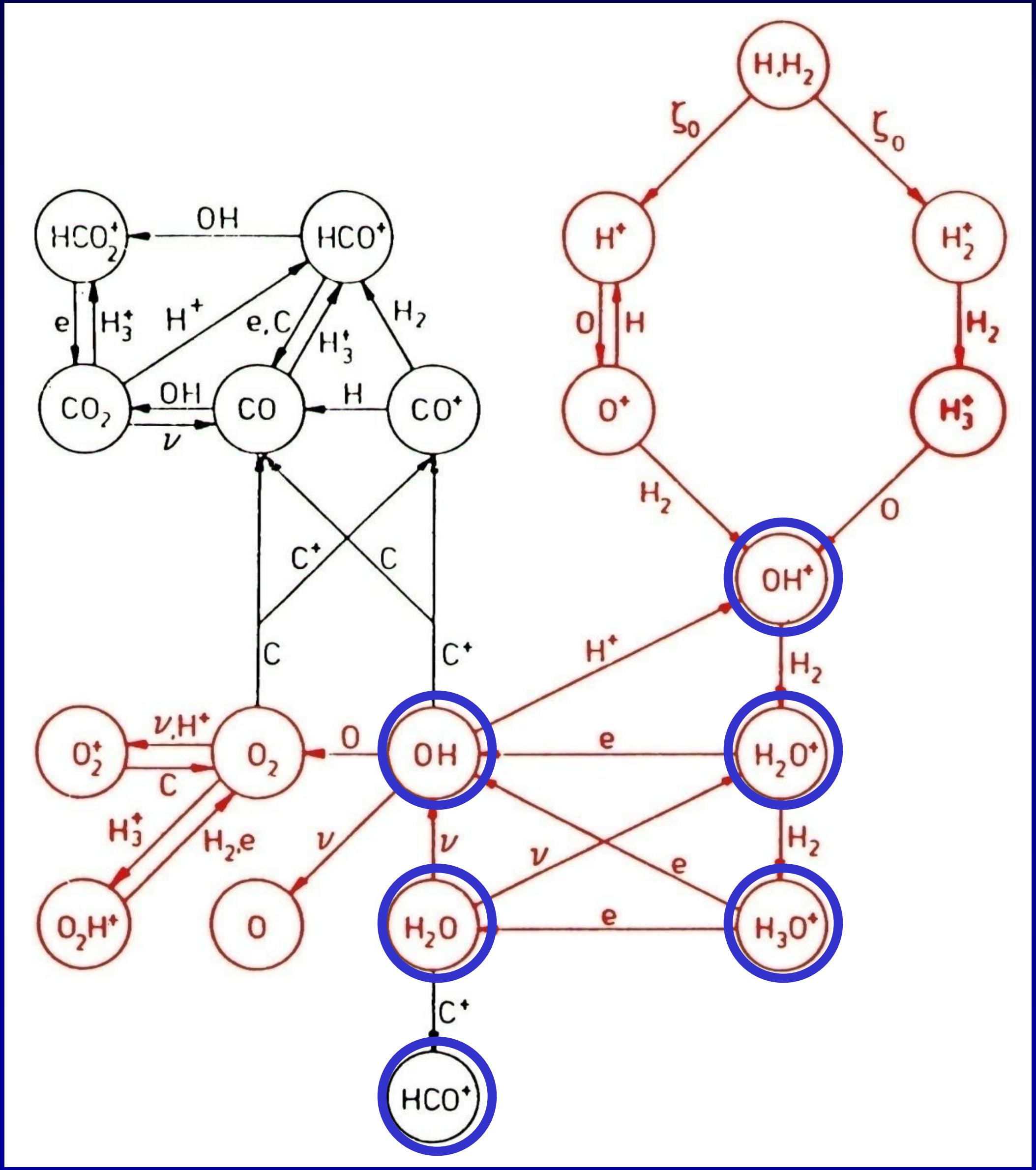


Dense gas: Diagnostics of UV (+ X-rays) heated outflow walls

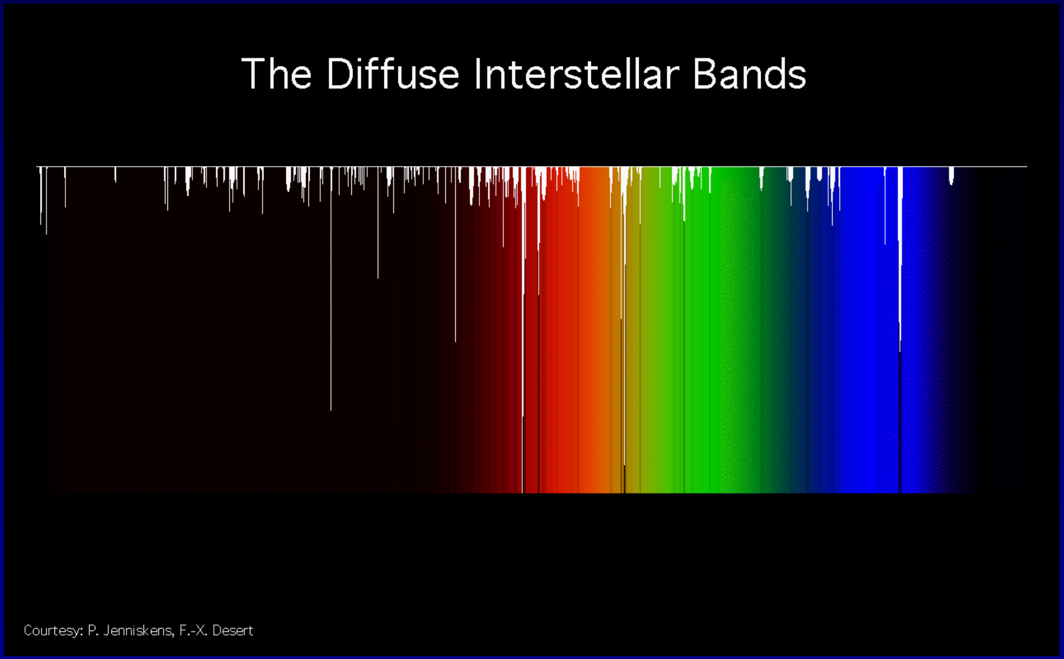
Diffuse gas: Warm gas with low H_2/H ratio

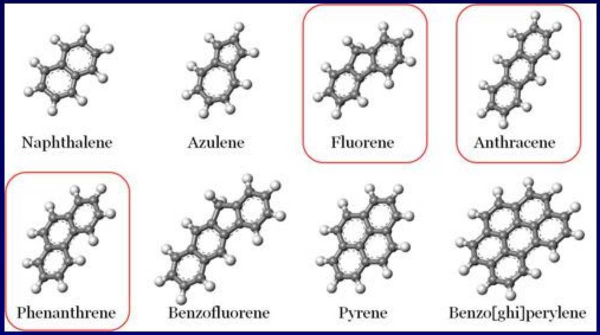
Benz +10, Gerin+10

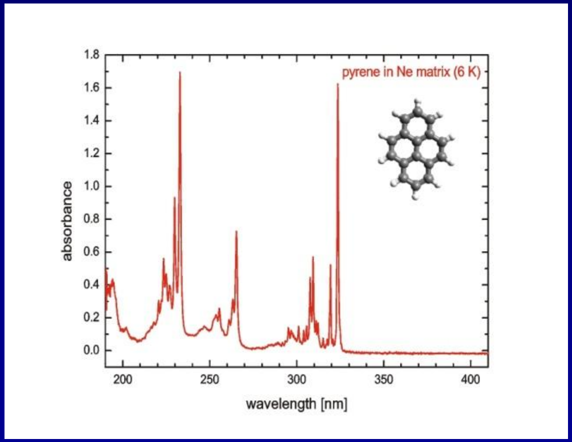
Gas-phase ion-molecule chemistry:
All key species in oxygen chemistry detected!



The DIB mystery



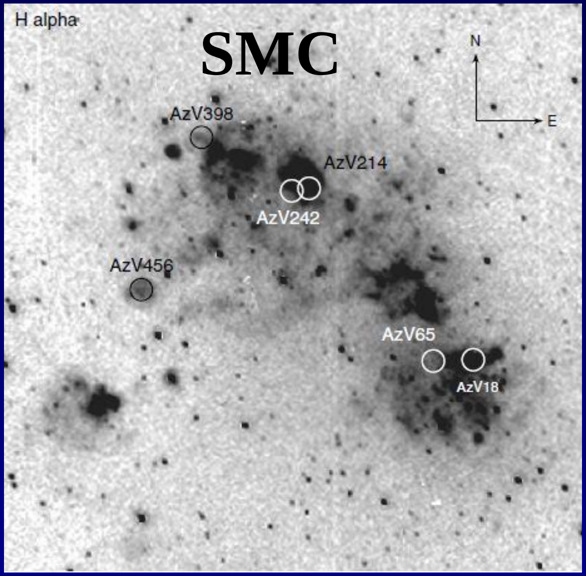


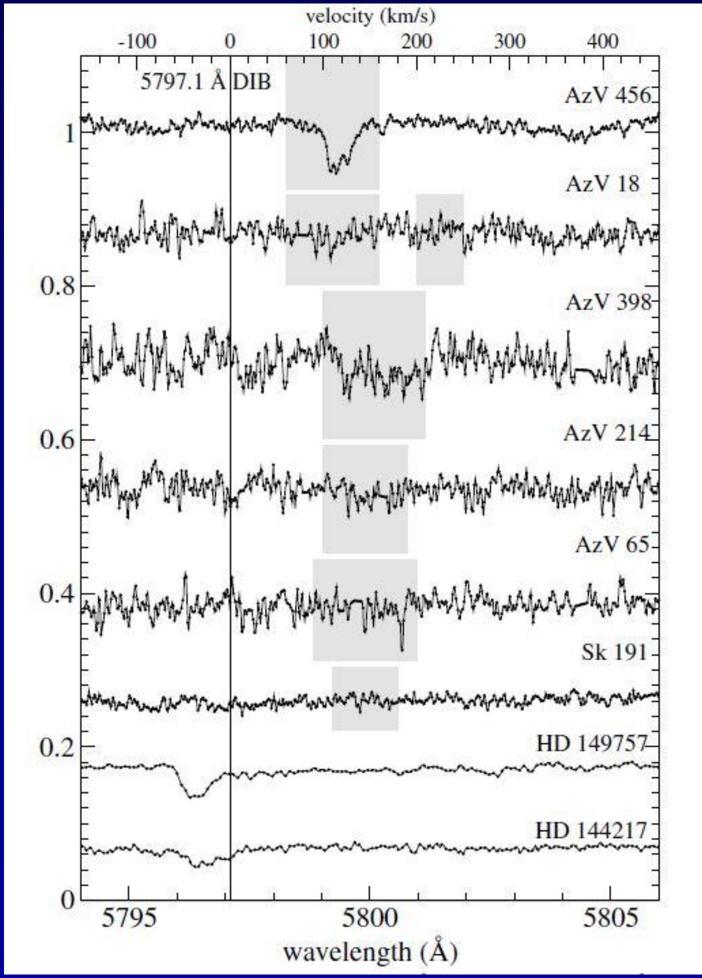


Gredel+2011

- Detected nearly 100 yr ago, no identification yet
- More than 200 DIBs known
- Many species ruled out, including simple PAHs

Extragalactic DIBs





Strength of DIBs depends on carbon abundance *and* UV field

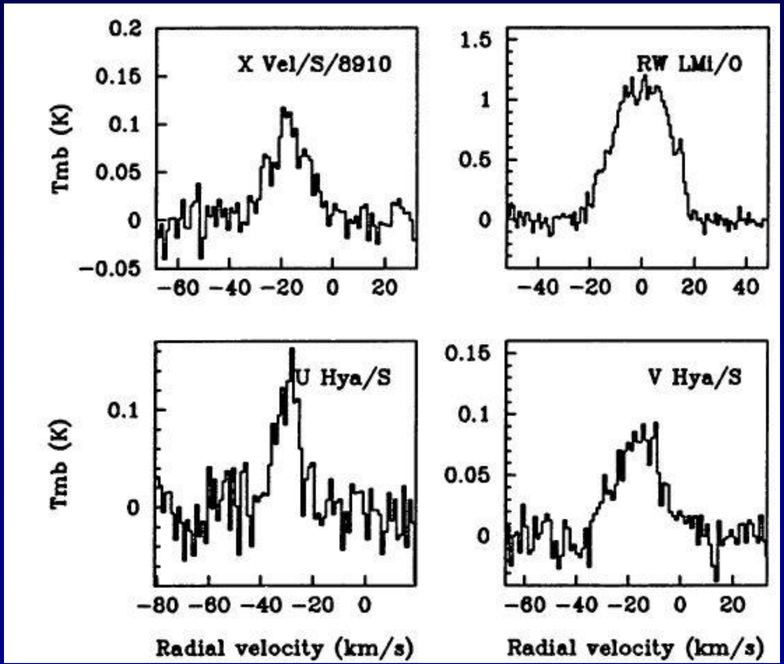
N. Cox+07
VLT-UVES

Molecules in dense clouds

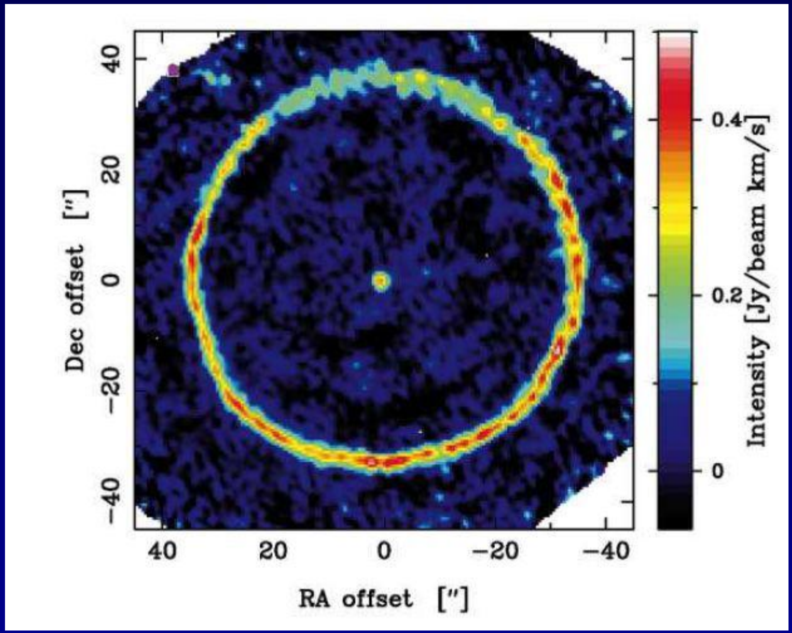
- Pioneering studies of southern clouds with SEST
- Both interstellar and circumstellar gas
- Key program on LMC/SMC

Circumstellar chemistry

HCN 1-0



TT Cyg PdBI

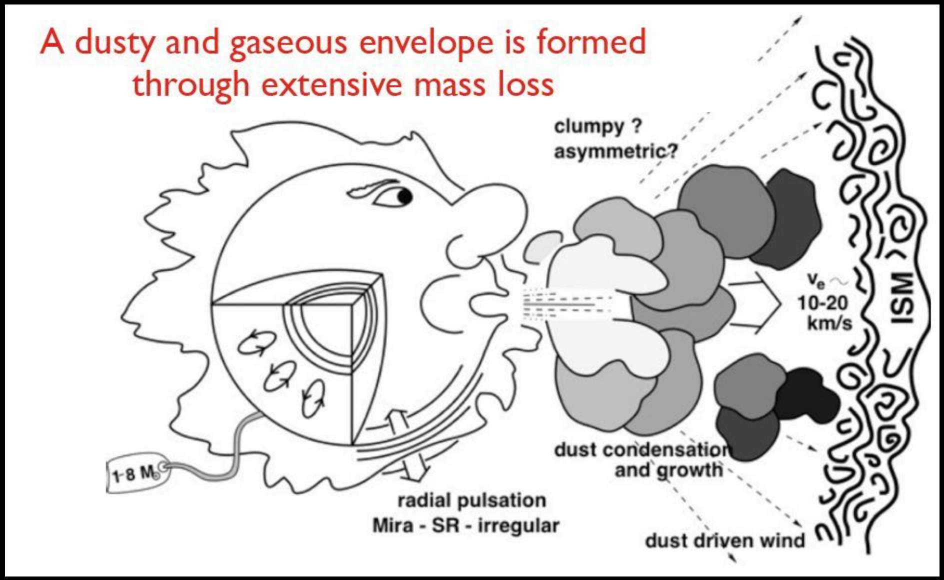


H. Olofsson +93,96,00,...

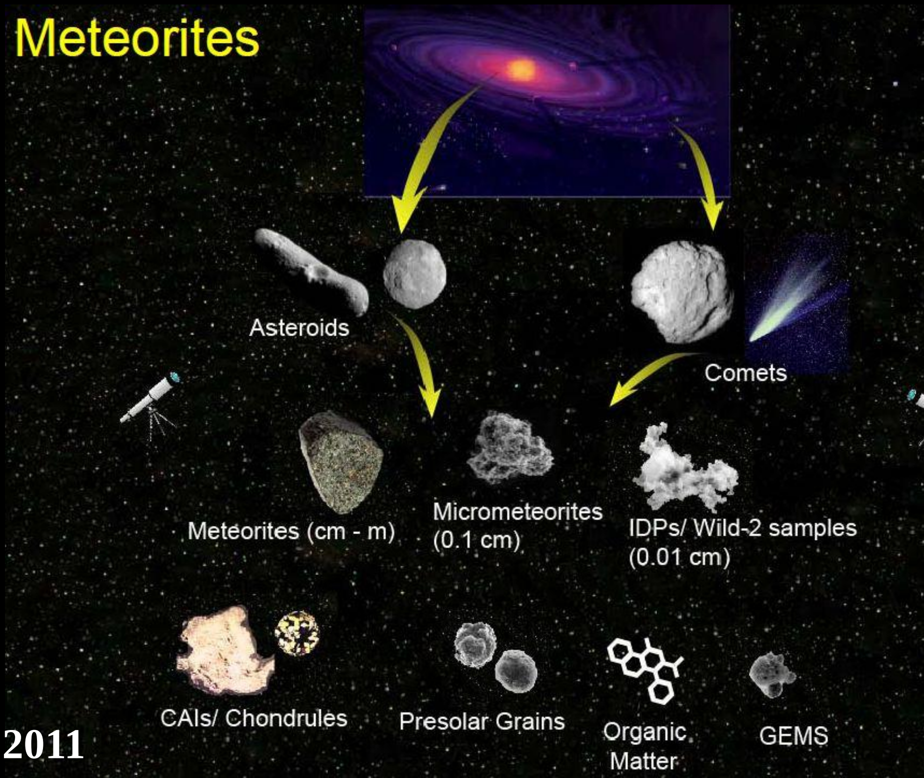
→ALMA!

- **Large surveys of C- and O-rich AGB stars; test of chemistry**
- **Isotope ratios $^{12}C/^{13}C$, $^{17}O/^{18}O$, $^{29}Si/^{28}Si$, ...**
- **Episodic mass loss rates**

Isotope ratios link origin solar system dust with AGB stars



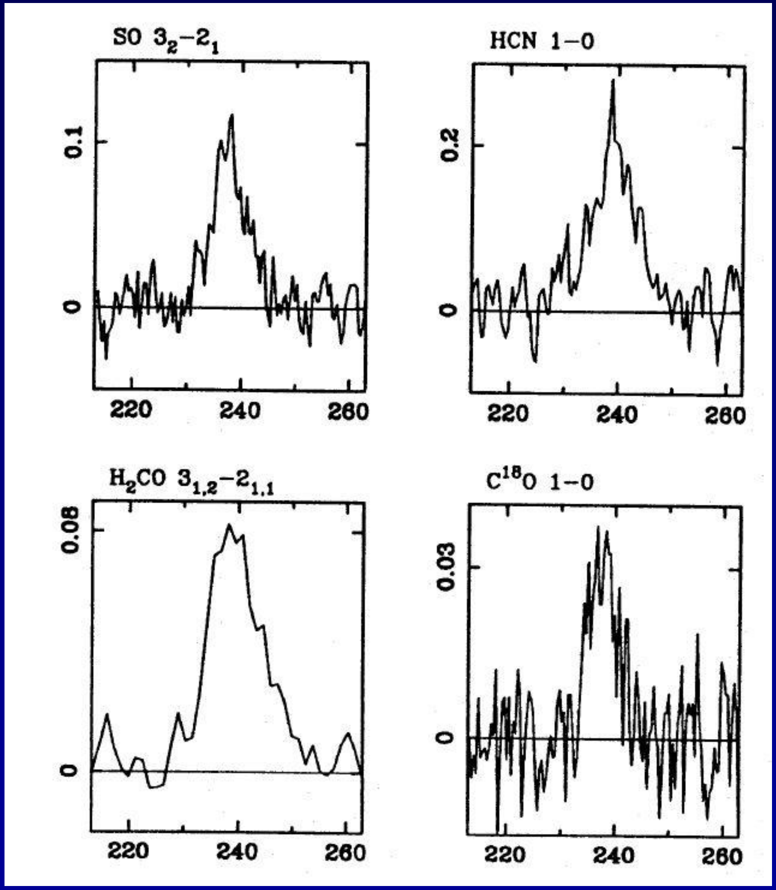
Olofsson 2011



Nittler 2011

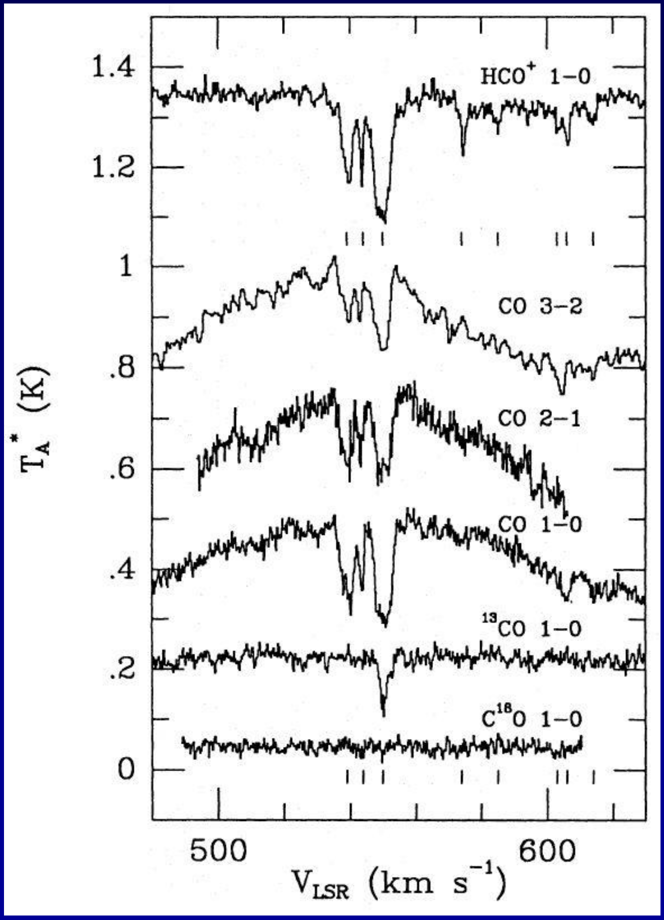
Extragalactic chemistry

N159 LMC



Johansson+94

Cen A



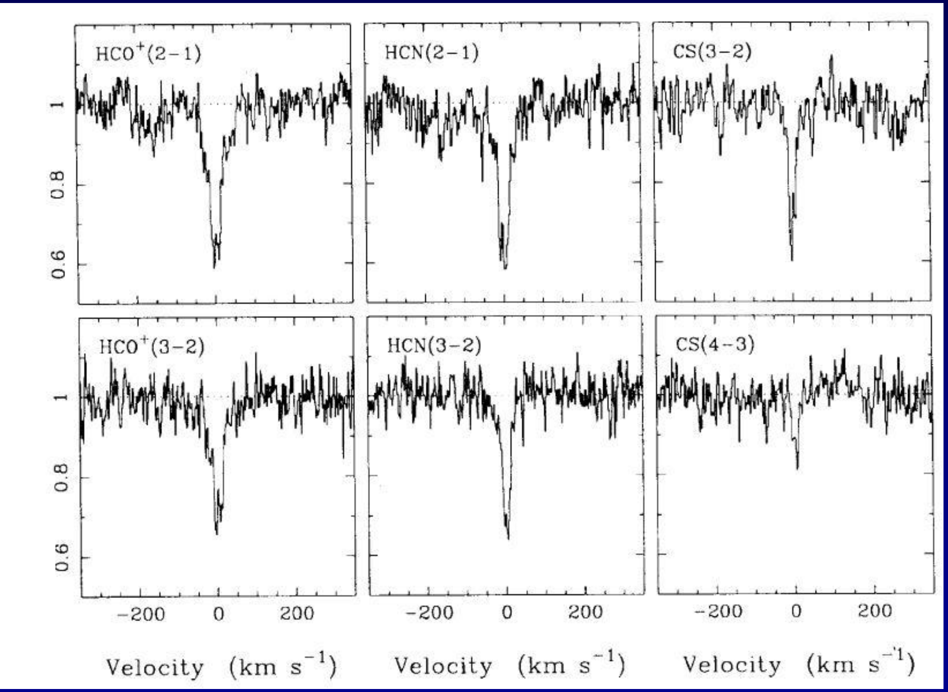
Israel+91

Circumnuclear ring + infalling clouds

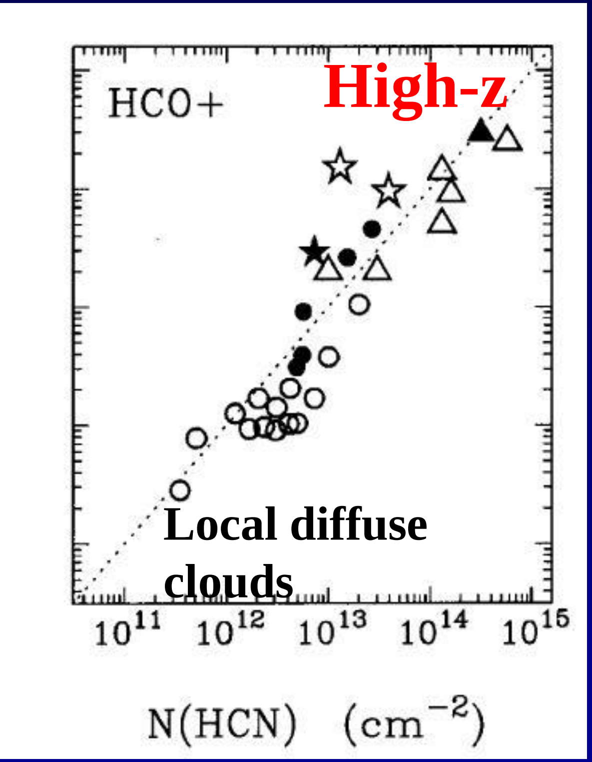
Abundances factor of 10 lower: cloud size?

Molecules at high z: absorption

PKS1830-211 z=0.88



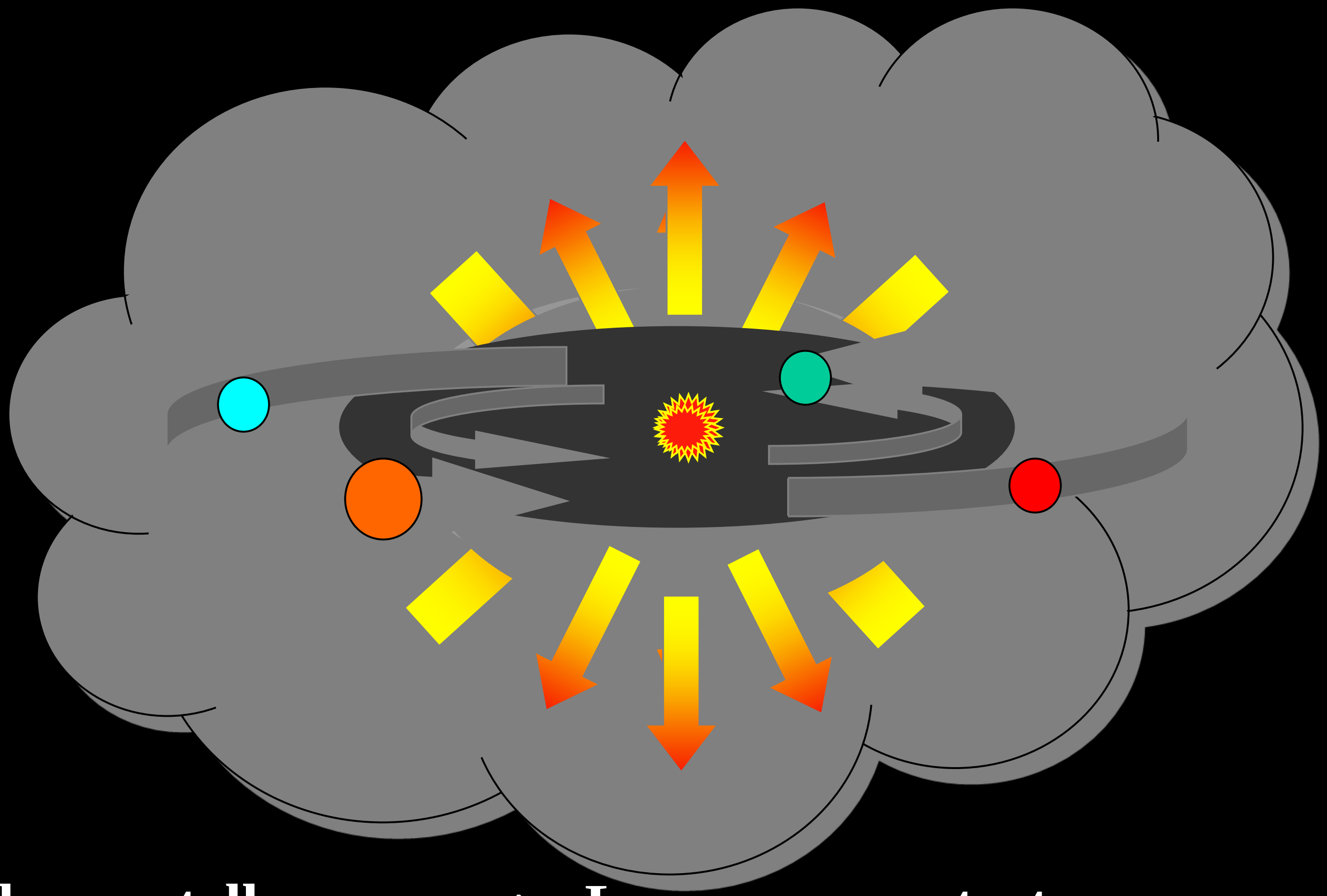
Combes & Wiklind 1996, 1997



Why no break diffuse – dense chemistry?

- **Relate local chemistry to high-z chemistry**
- **Limits on unobservable molecules from Earth: O_2, H_2O**

Follow water and organics during star and planet formation



Dark pre-stellar cores → Low-mass protostars → Disks

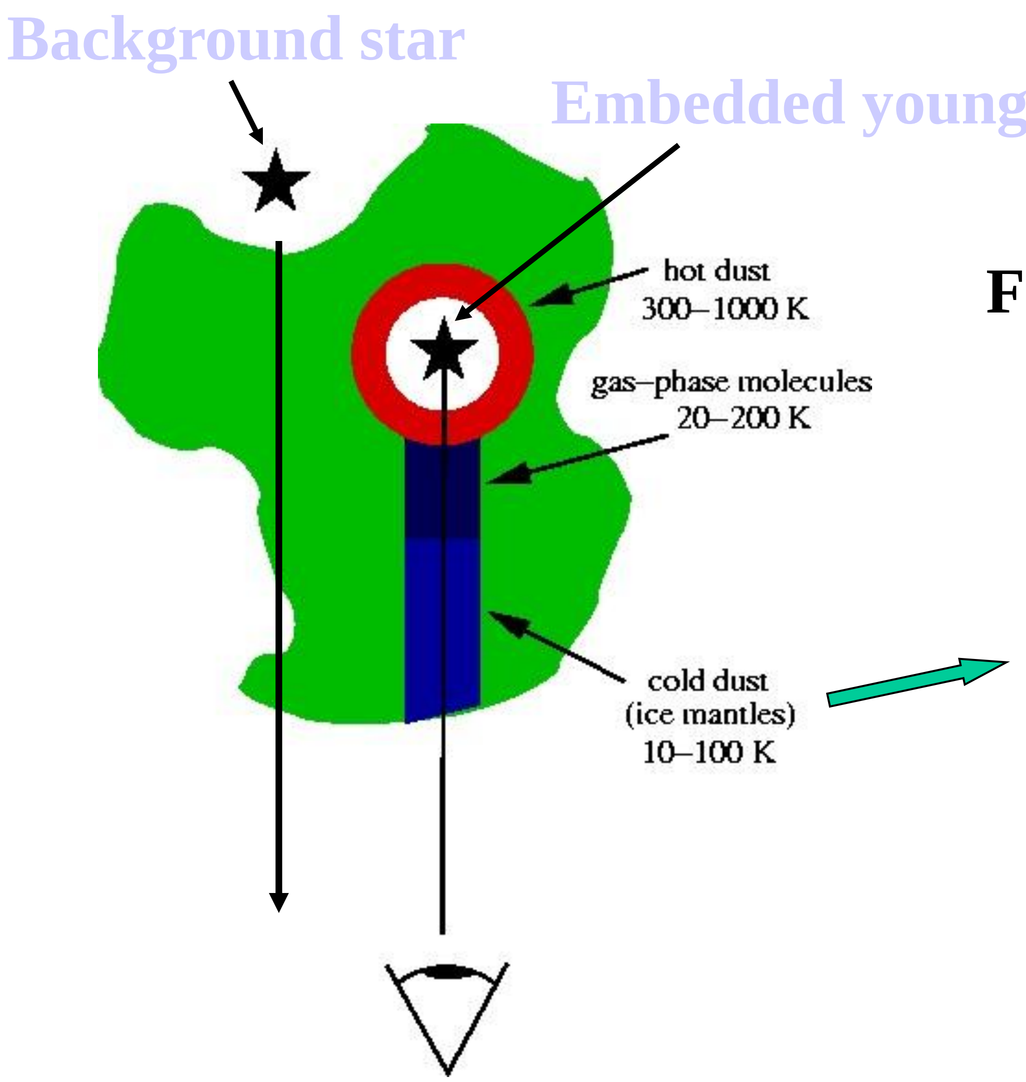
Star-forming regions: Gas-grain chemistry

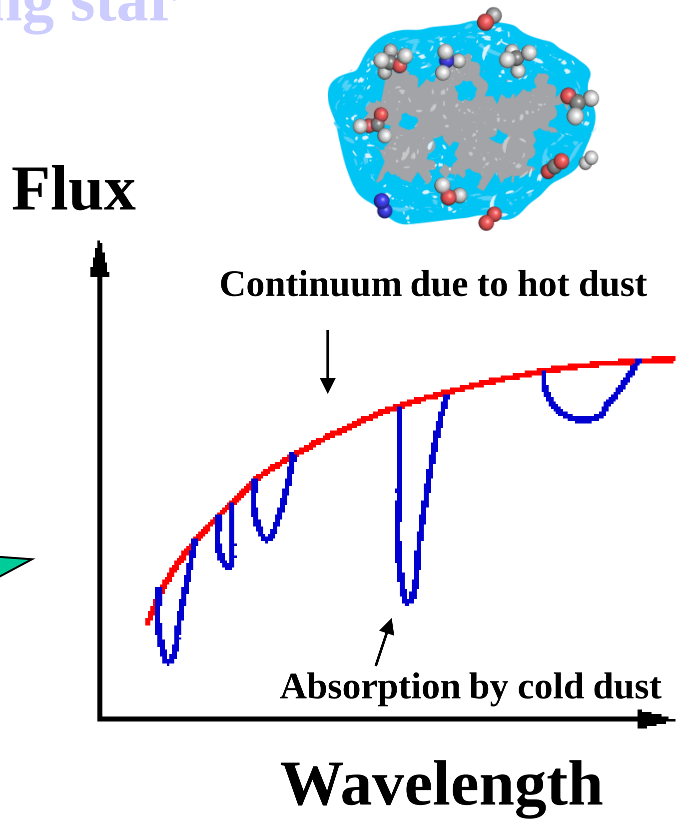
Taurus filament
APEX-LABOCA

VLT

APEX

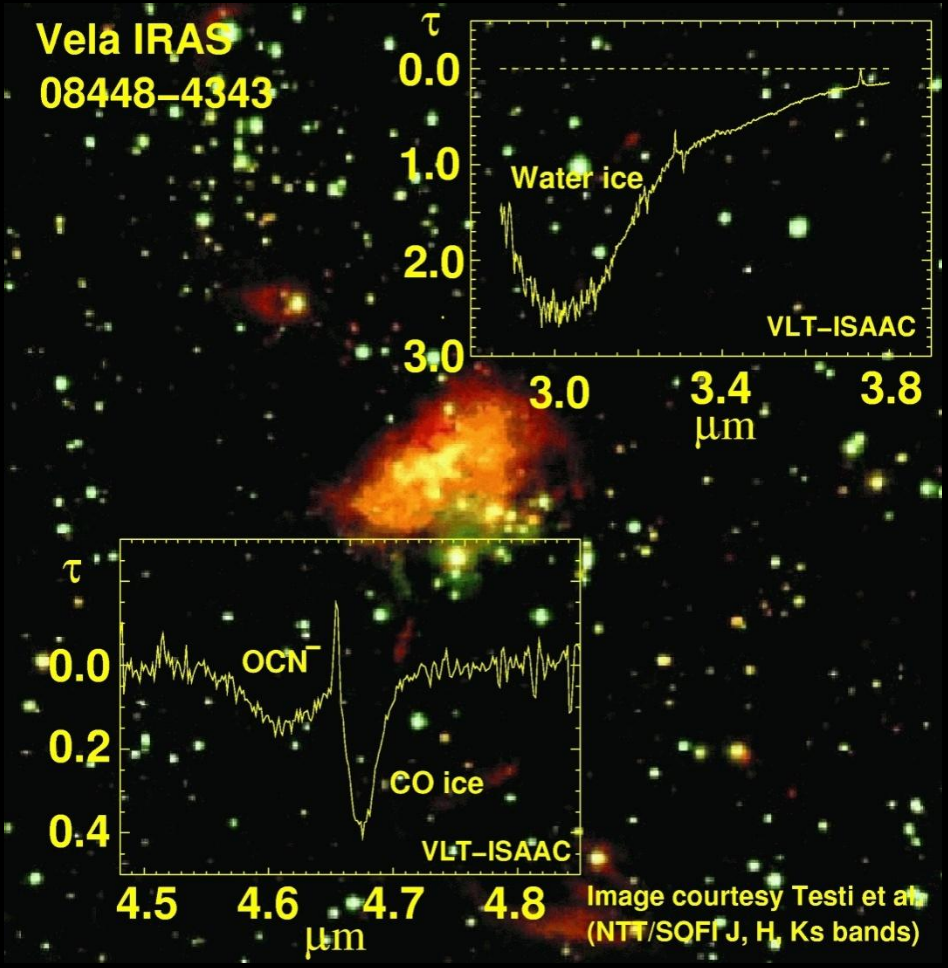
Infrared: absorption





Infrared: vibrational transitions of gases *and* solids

H_2O, CO and other ice species



- Large VLT-ISAAC program to survey ~50 low-mass southern protostars at L and M-band

vD+ 02
Thi +05
Van Broekhuizen +05

Solid CO evolution

Collings, Fraser et al. 2003

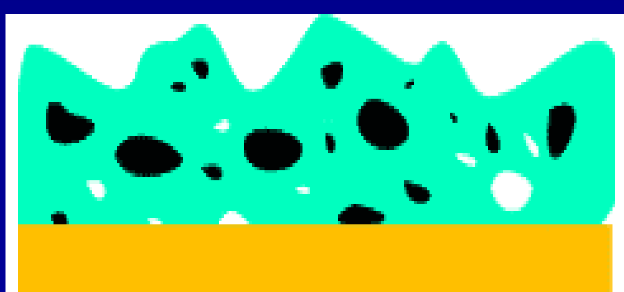
CO

H_2O

< 10 K

Ices are layered

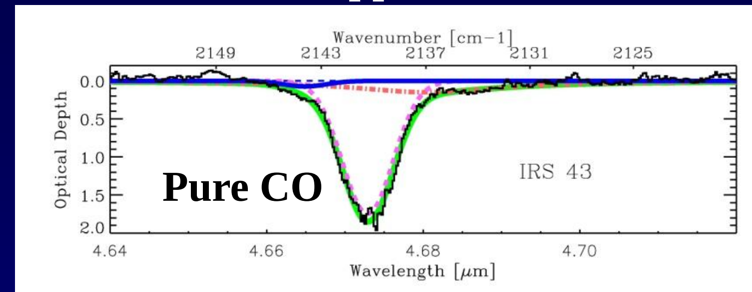
10 - 20 K

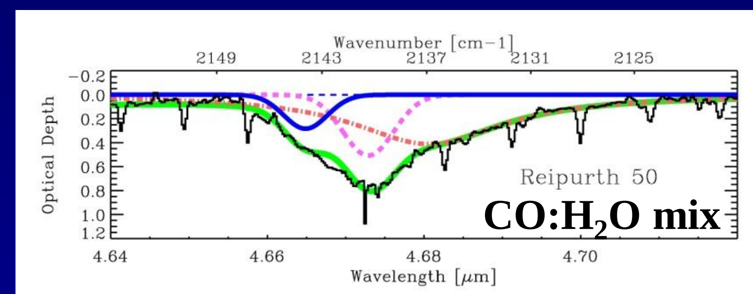


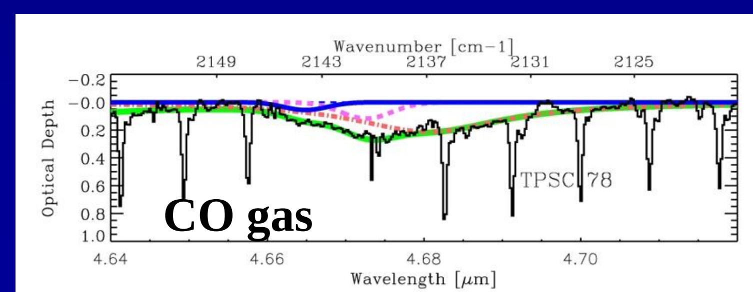
30 - 70 K

Pontoppidan et al. 2003

$R \sim 10^4$





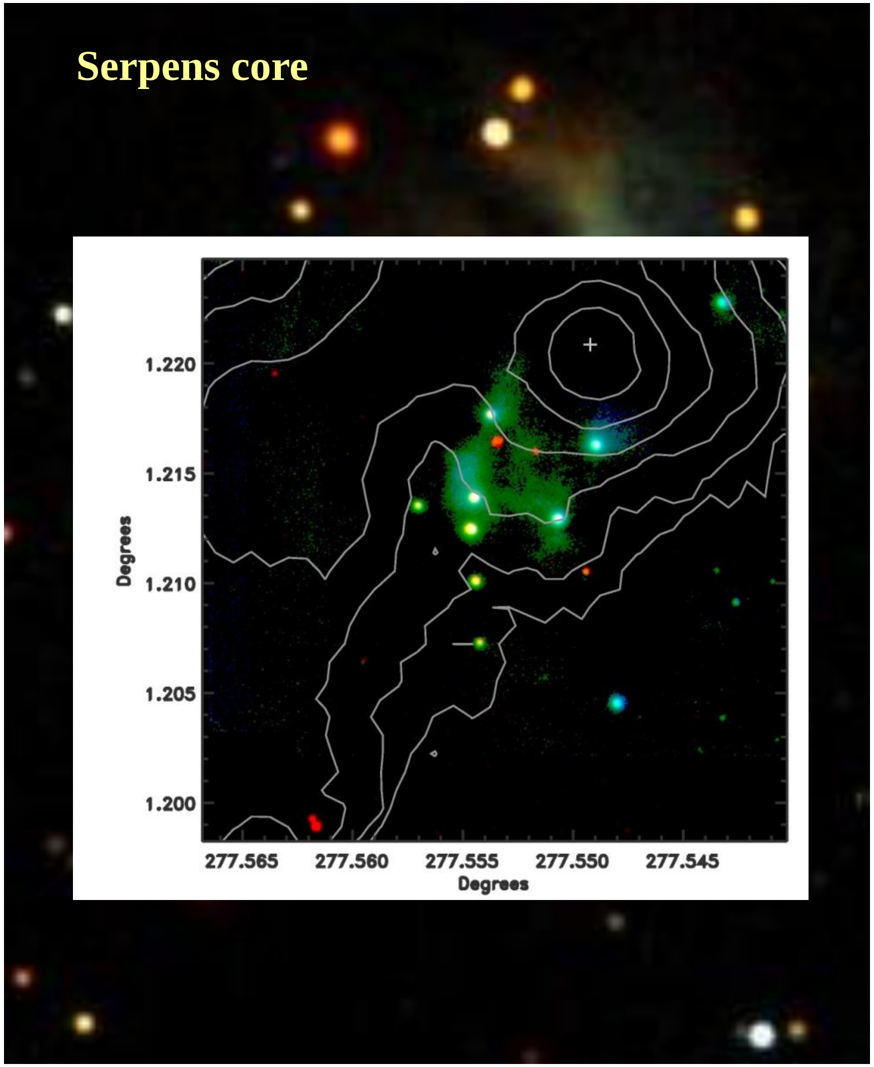


T

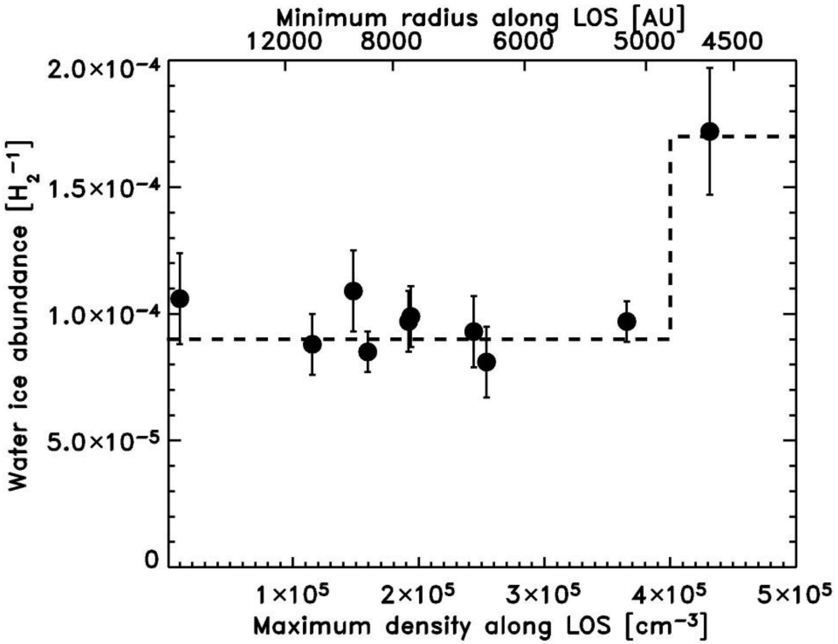
Use solid CO profile and gas/ice as evolutionary indicators

First ice map on 1000 AU scales

VLT-ISAAC



2Mass



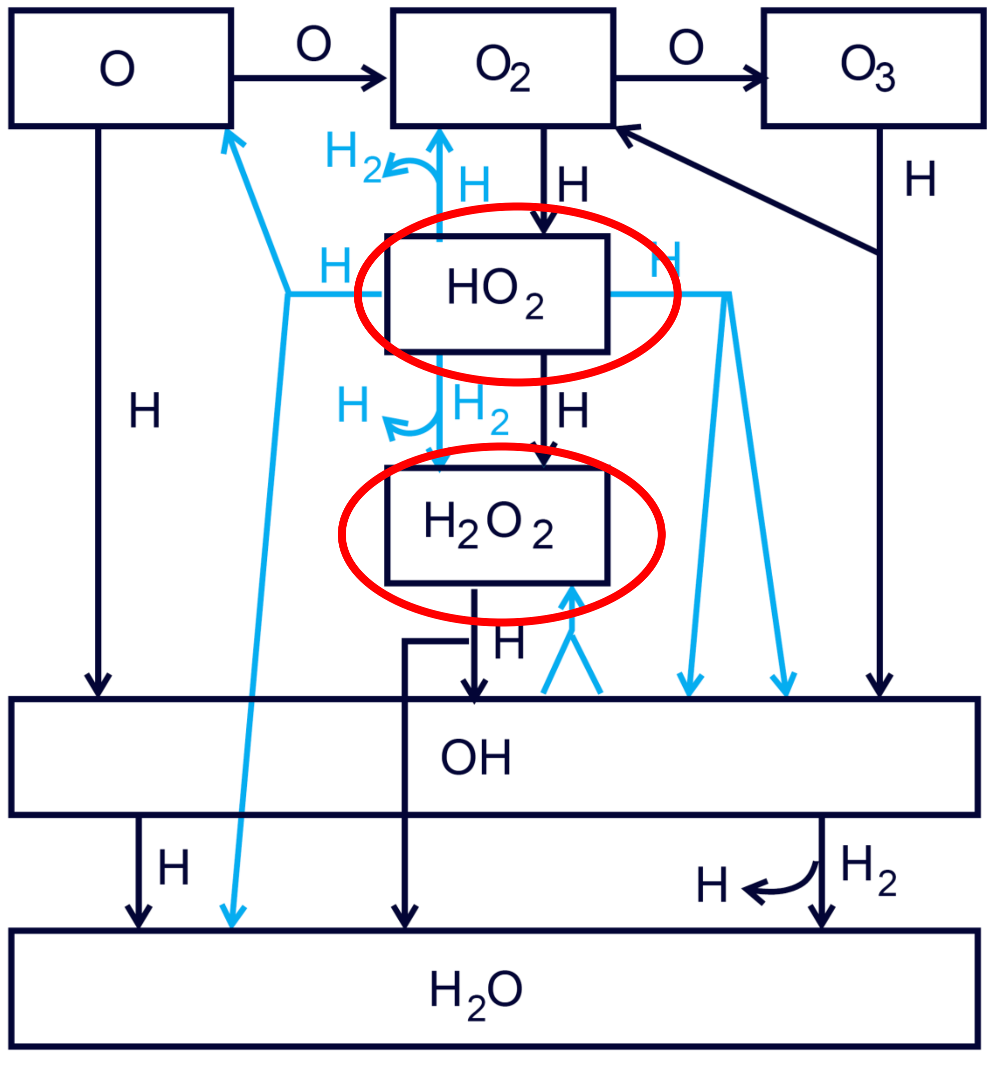
-50% of O frozen out as H_2O ice!

- High abundance of CH_3OH ice

Pontoppidan et al. 2004

How to make water ice

A success story lab-observations



Tielens & Hagen82

Ioppolo+08,10
Cuppen+10
Watanabe+

Detailed laboratory experiments reveal multiple routes at 10 K

Detection of interstellar H_2O_2 and HO_2

Solid-state astrochemistry has become predictive!

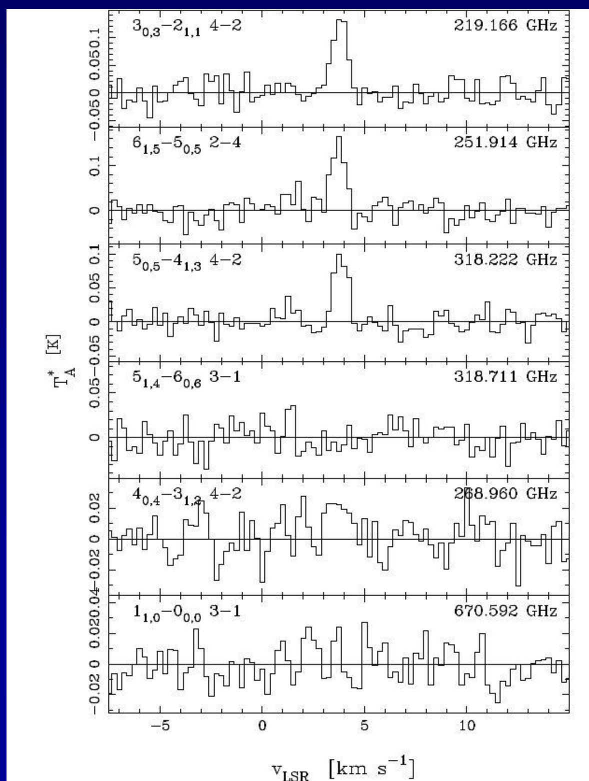
Detection of interstellar hydrogen peroxide ★

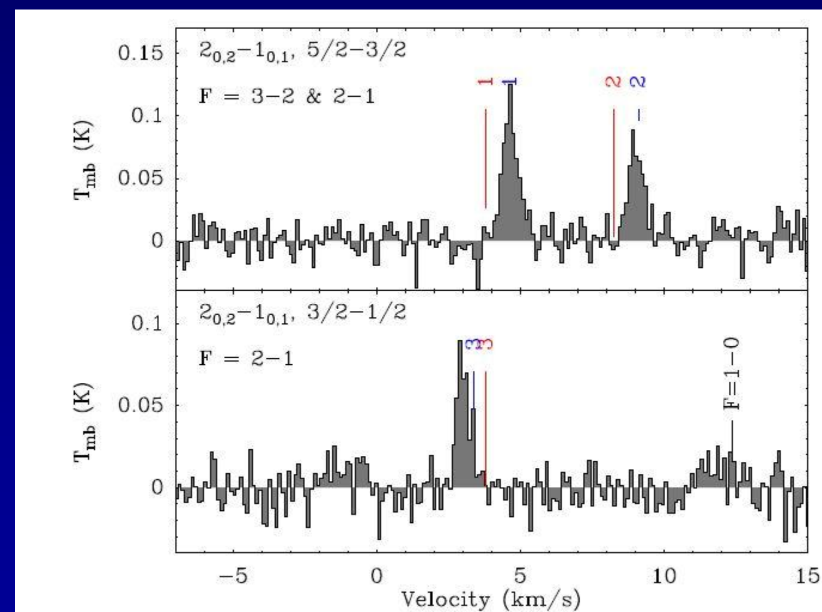
P. Bergman[1], B. Parise[2], R. Liseau[3], B. Larsson[4], H. Olofsson[1], K. M. Menten[2], and R. Güsten[2]

Detection of the hydroperoxyl radical HO_2 toward ρ Oph A★

Additional constraints on the water chemical network

B. Parise[1], P. Bergman[2], and F. Du[1★★]



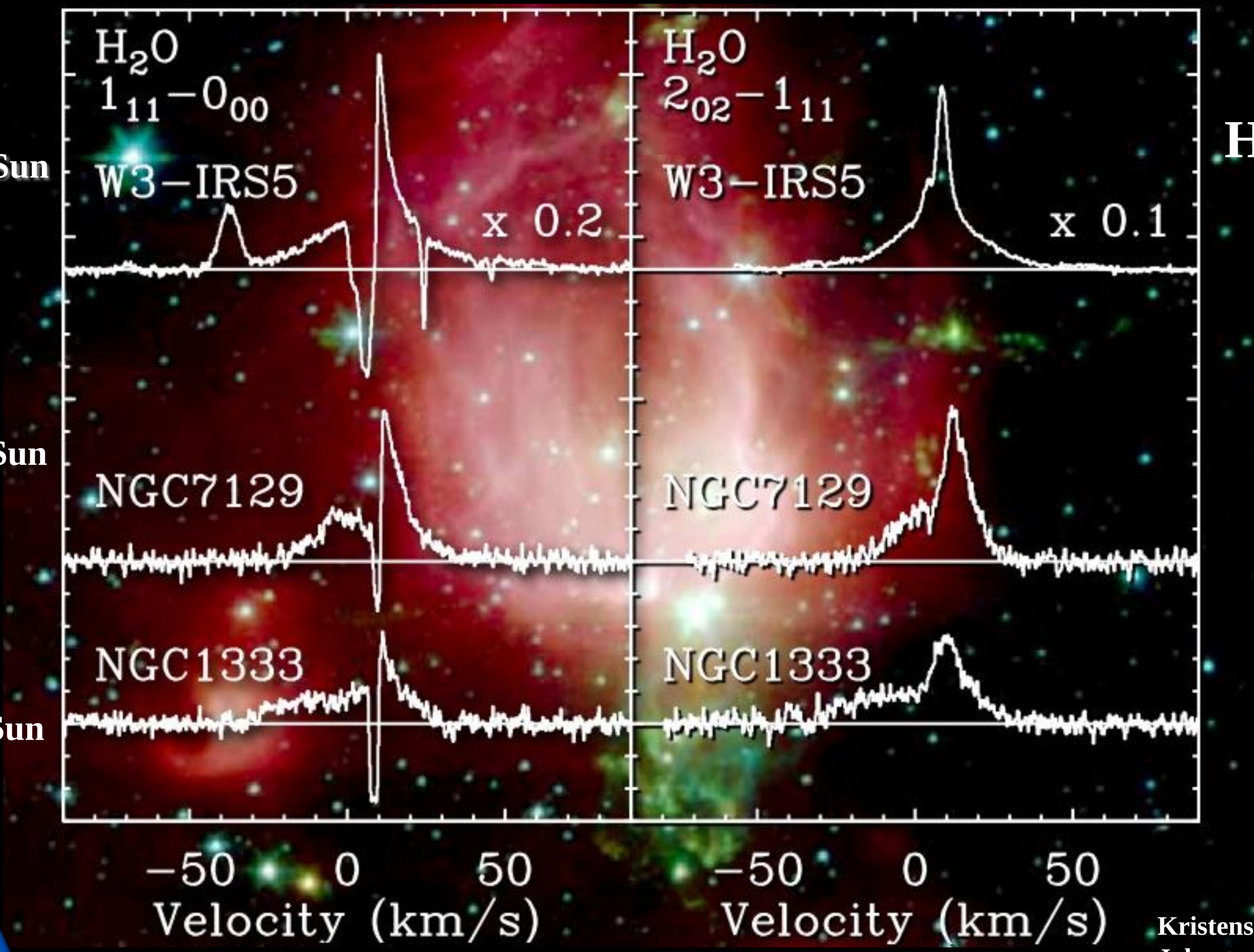


Bergman et al. 2011

Parise et al. 2012

APEX

Water: From low to high mass protostars



10^5 L_{Sun}

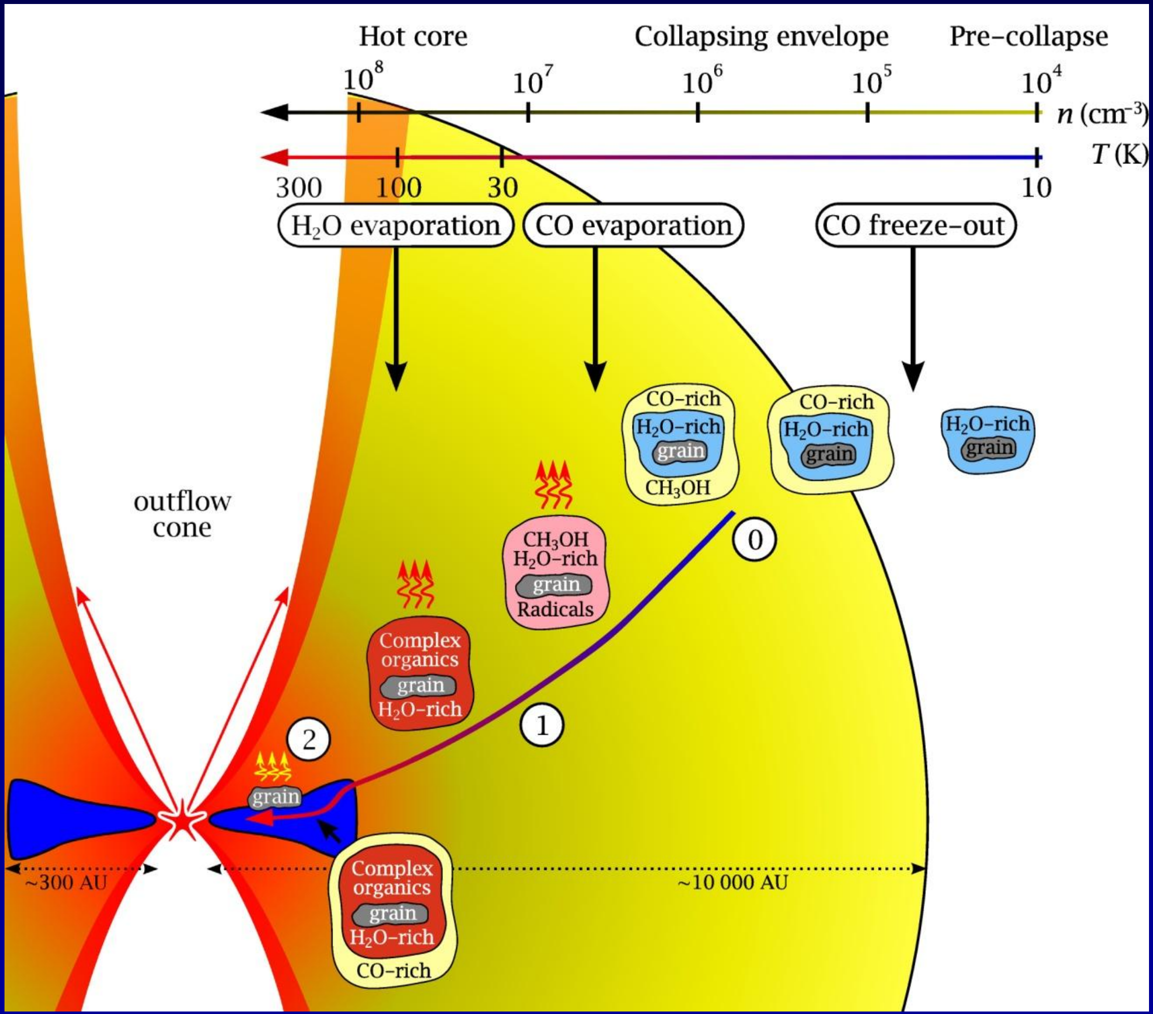
430 L_{Sun}

20 L_{Sun}

Herschel

Kristensen+ 2010
Johnstone + 2010
Chavarria+ 2010
vD+2011

Journey of water and organics from cores to planet-forming disk



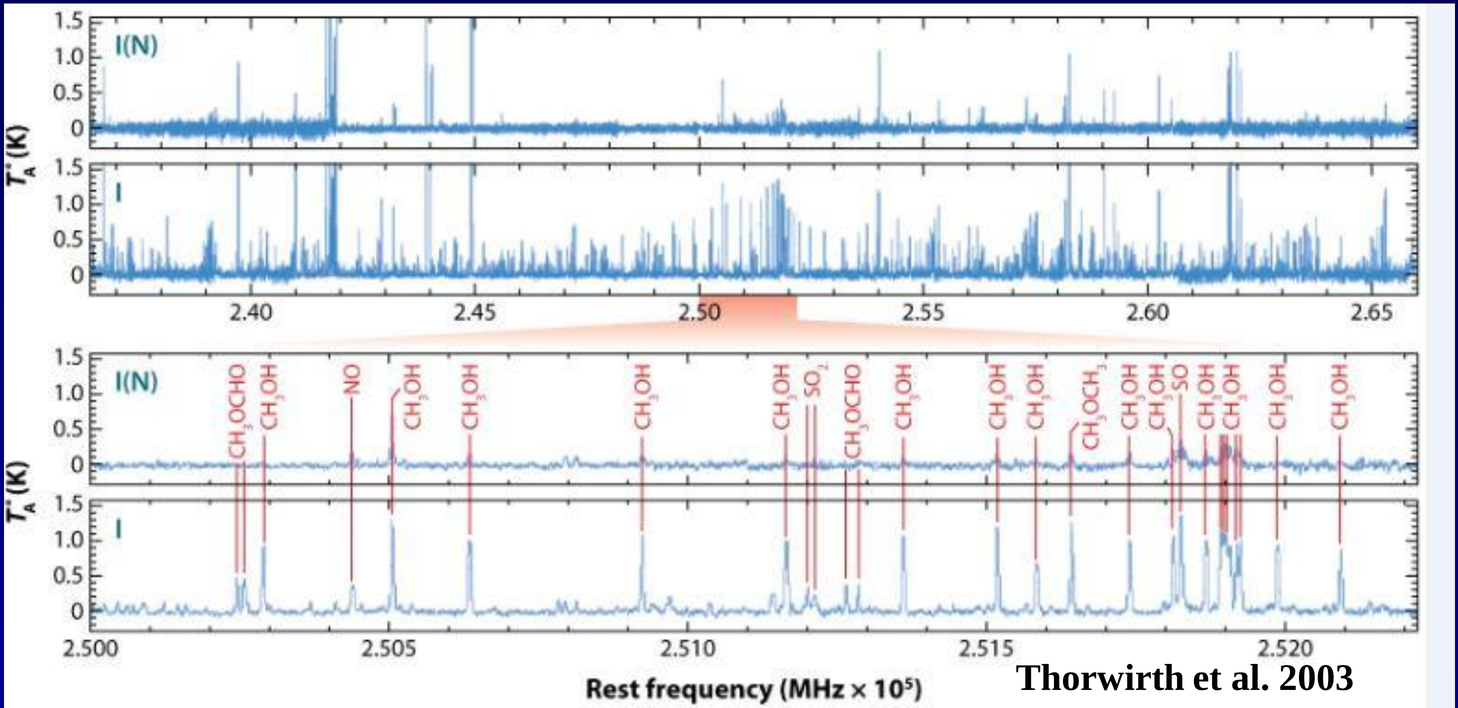
Herbst & vD
ARA&A 2009

Visser et al. 2009

- Molecules evaporate from dust grains when heated by protostars → hot core chemistry

Chemical diversity massive YSOs

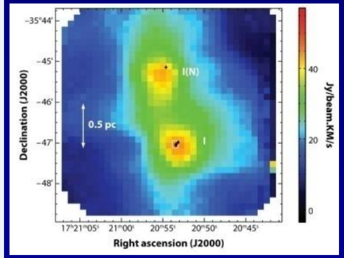
SEST NGC 6334 I and I(N) 10^5 L_{sun} 1.7 kpc



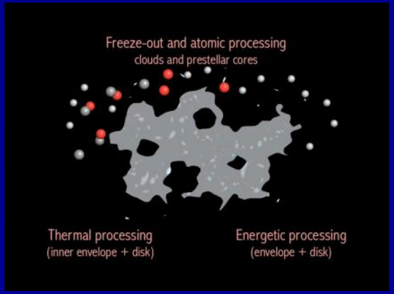
Thorwirth et al. 2003

Line poor

Line rich

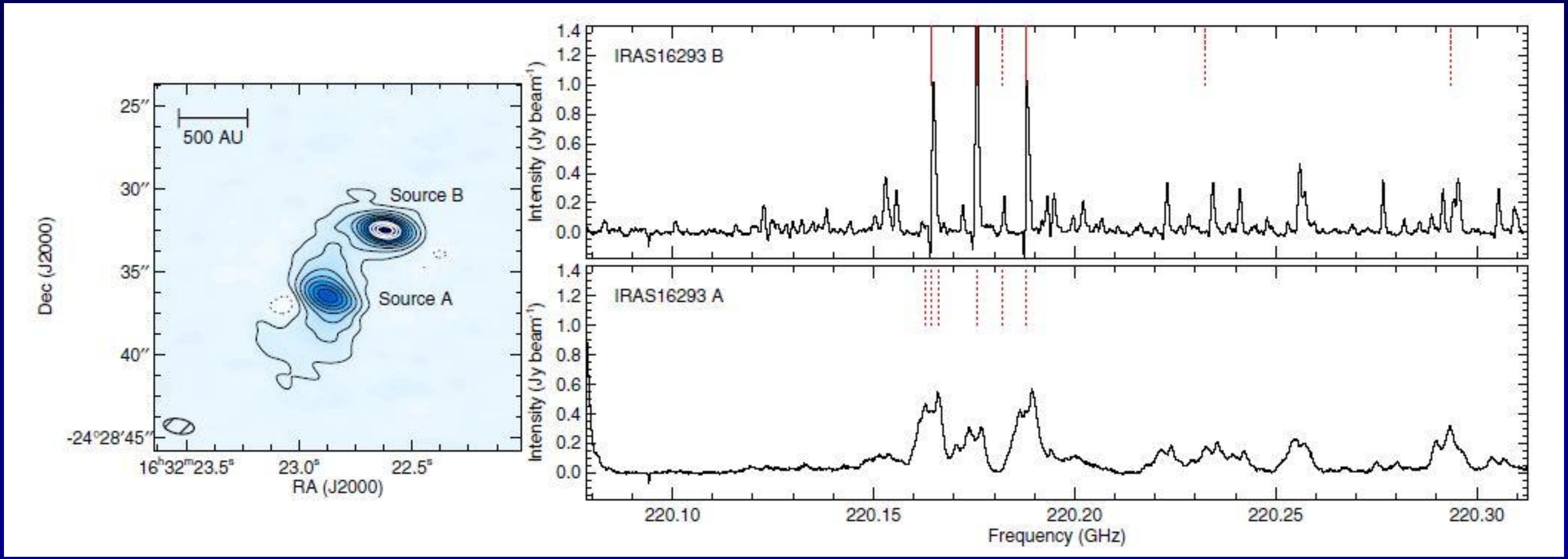


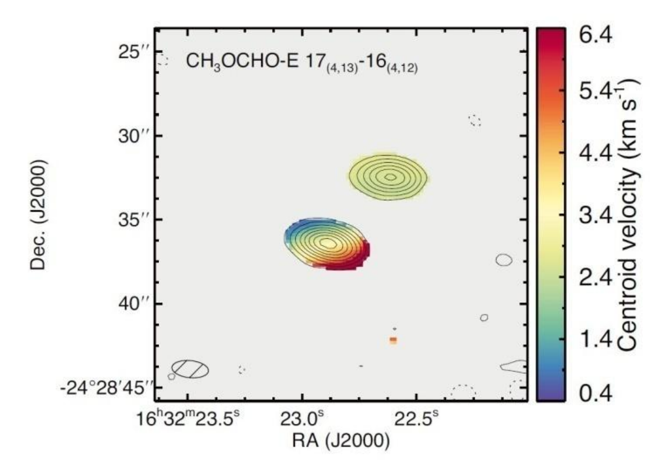
- **Most massive YSOs characterized by rich spectra but not all**
- **NGC 6334 source I much richer than source I(N), even though only 0.5 pc apart**
- **Emission arises from ~1” (1000 AU radius)**



Zoom in with ALMA on *solar-mass* protostars

IRAS 16293 -2422 27 L_{sun} 125 pc

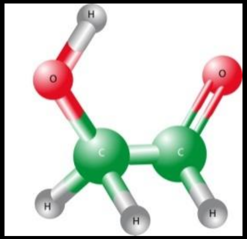


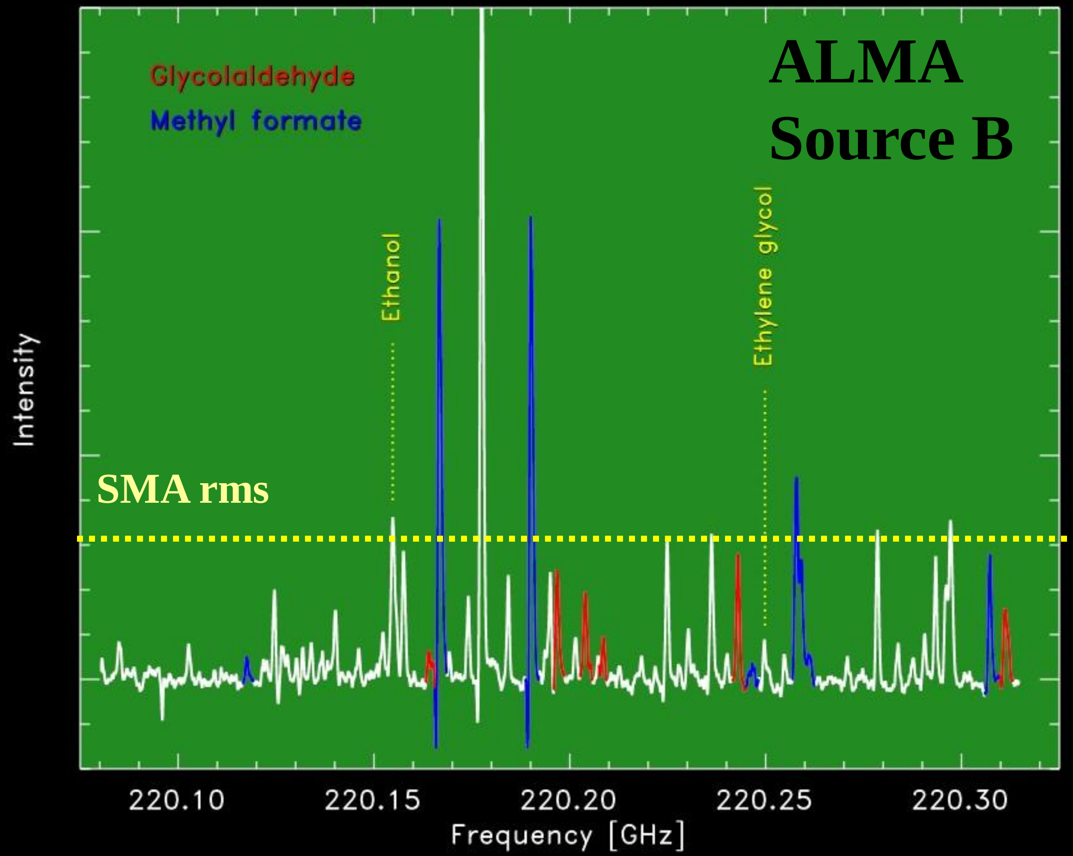


Pineda et al. 2012
Jørgensen et al. 2011, 2012

- Protobinary source, with different chemistries sources A and B

Hunt for complex molecules



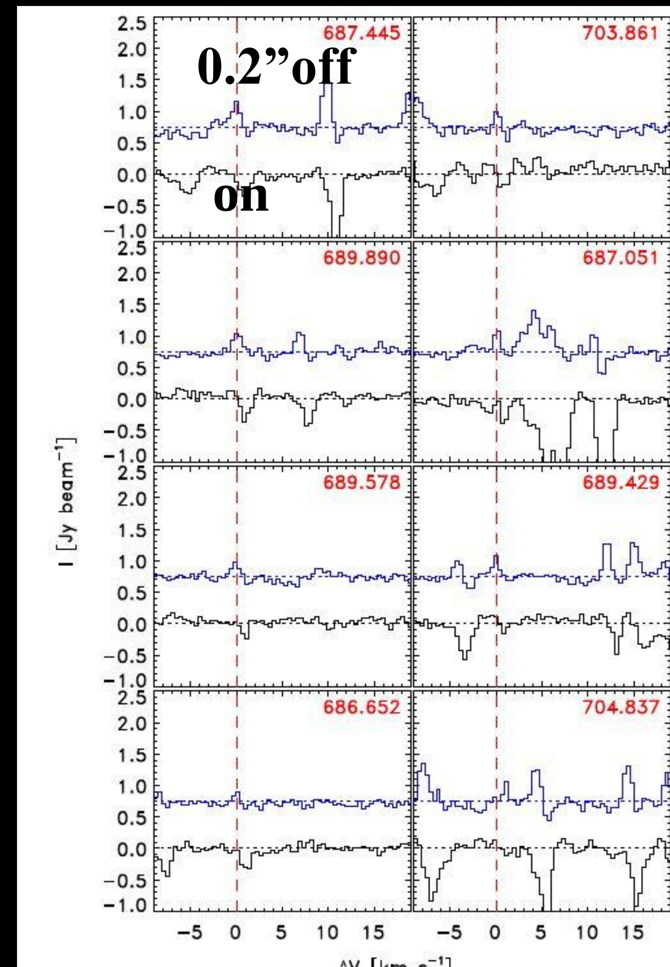


-LTE model at 300 K, some lines from vibrationally excited levels

- Factor 10 more lines than SMA data at this frequency

Jørgensen+12

Glycolaldehyde confirmed by Band 9 data (13 lines total)



Sweet ALMA result!

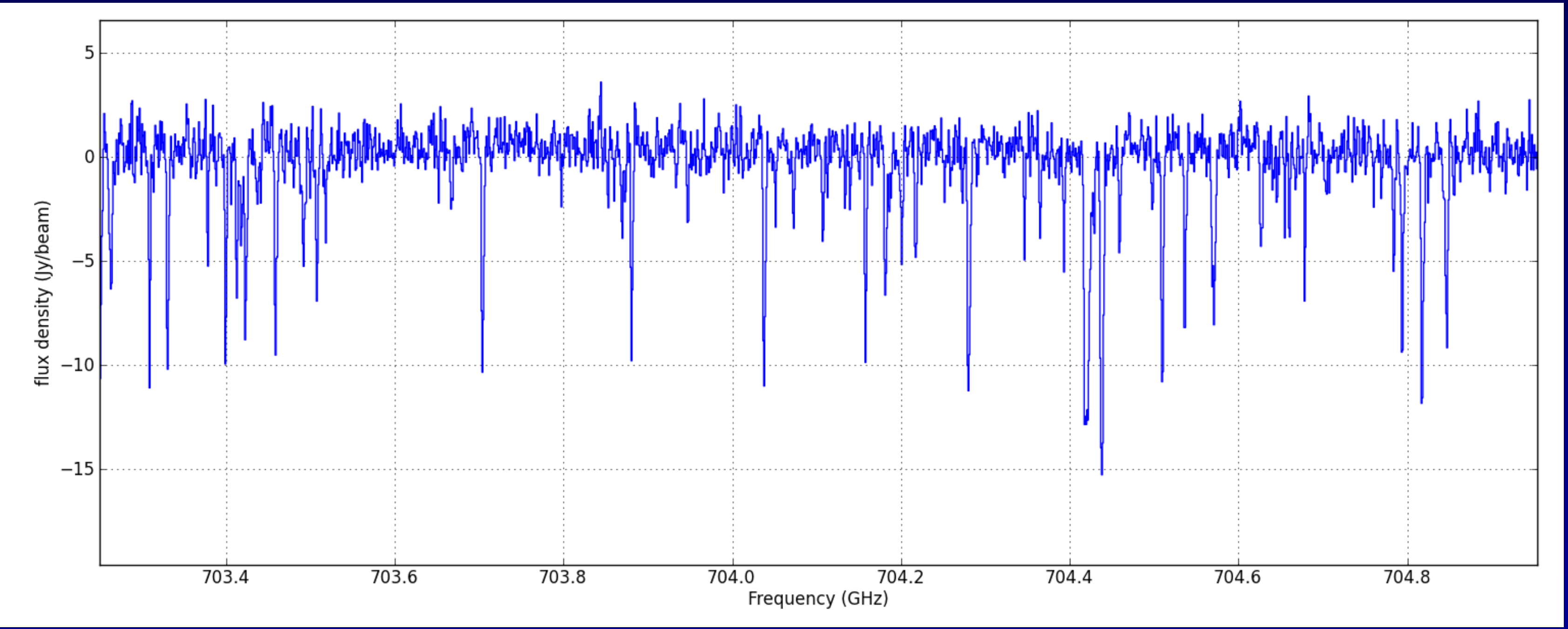
Jørgensen+12

- Methylformate : glycolaldehyde ~10:1
- Glycolaldehyde : ethylene glycol ~2-3
- Consistent with lab processing of CH_3OH ice (Öberg et al. 2009)

Sourze size ~20 AU

The astrochemistry revolution

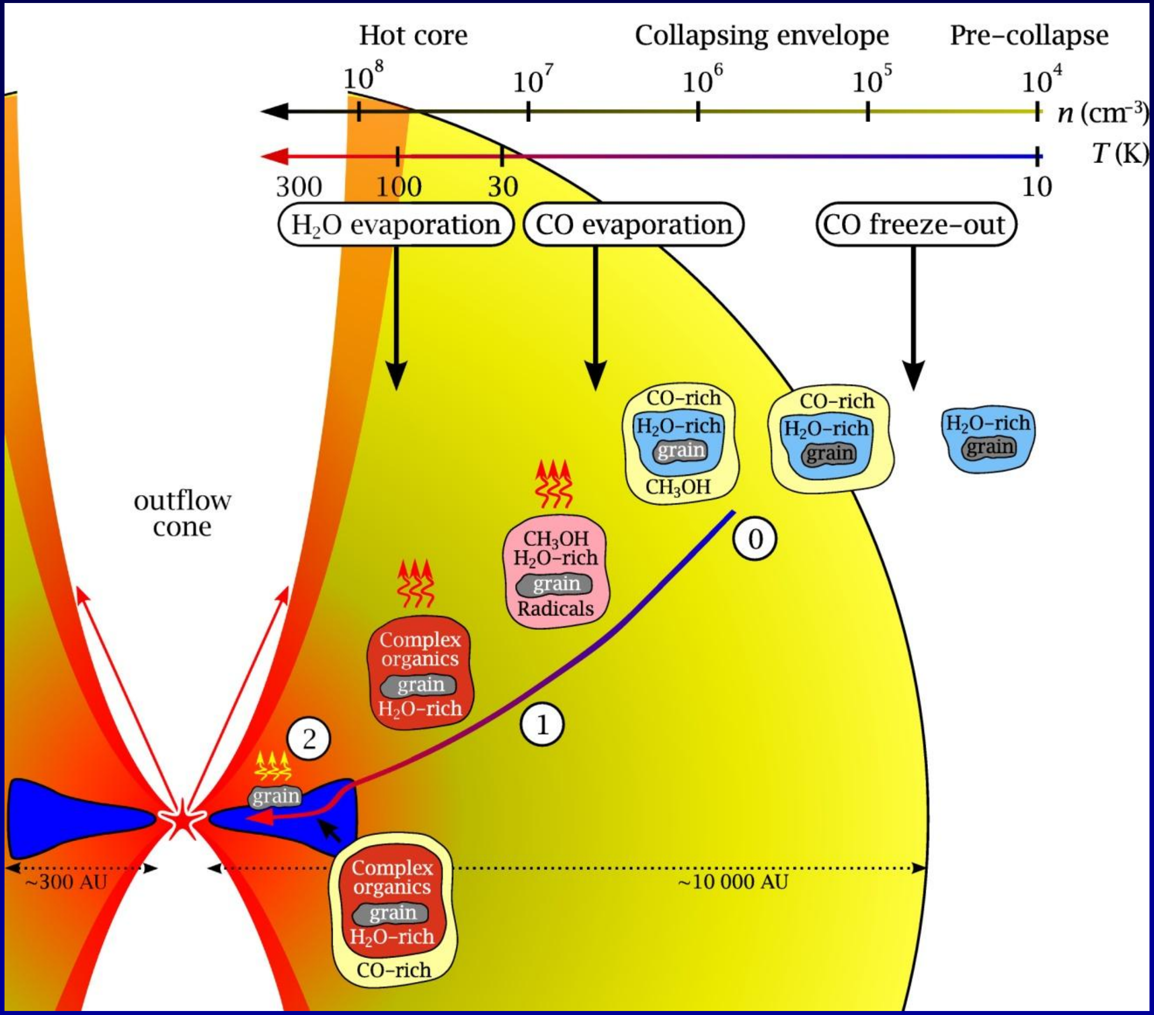
IRAS 16293 -2422B ALMA Band 9 spectrum



-Many Unidentified lines, typically 50% of lines!

- Lots of (boring) laboratory work needed to identify them

Journey of water and organics from cores to planet-forming disk

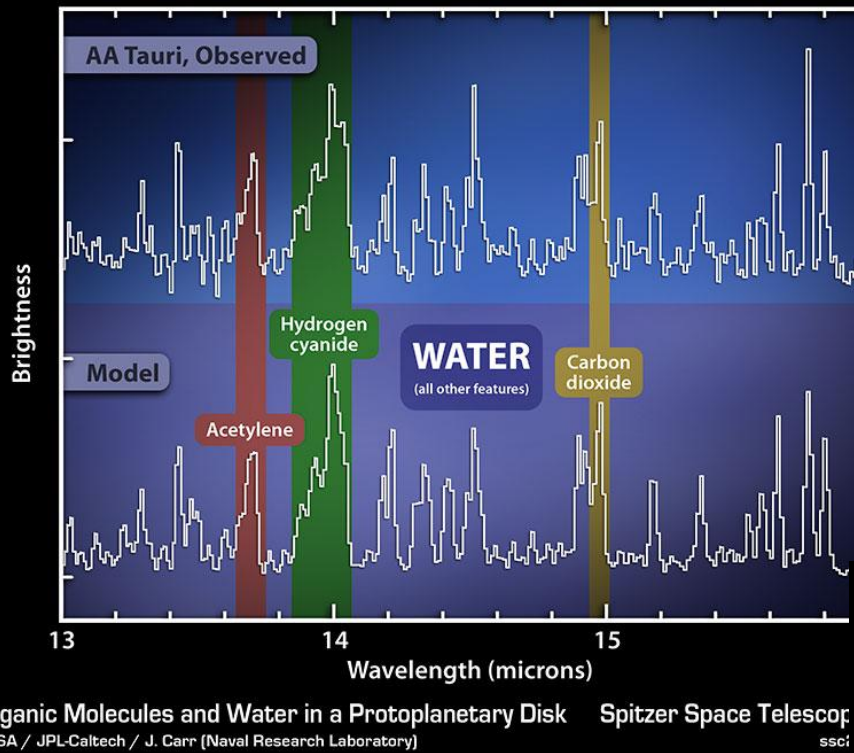


Herbst & vD ARA&A 2009

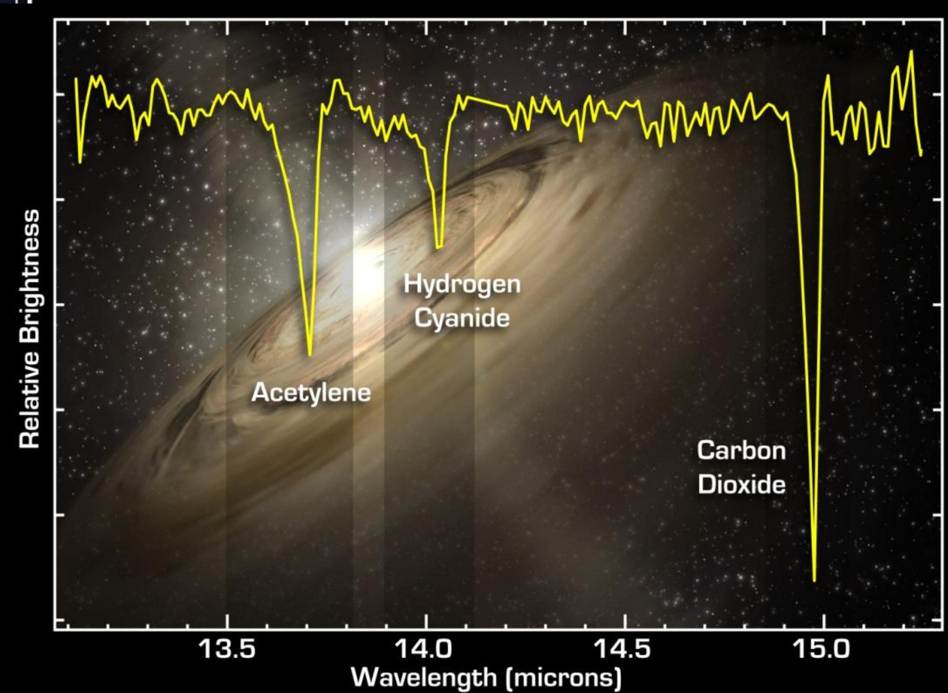
Visser et al. 2009

- Some fraction of ices and complex organics enters disk

Hot water and organics in inner few AU of disks: mid-IR

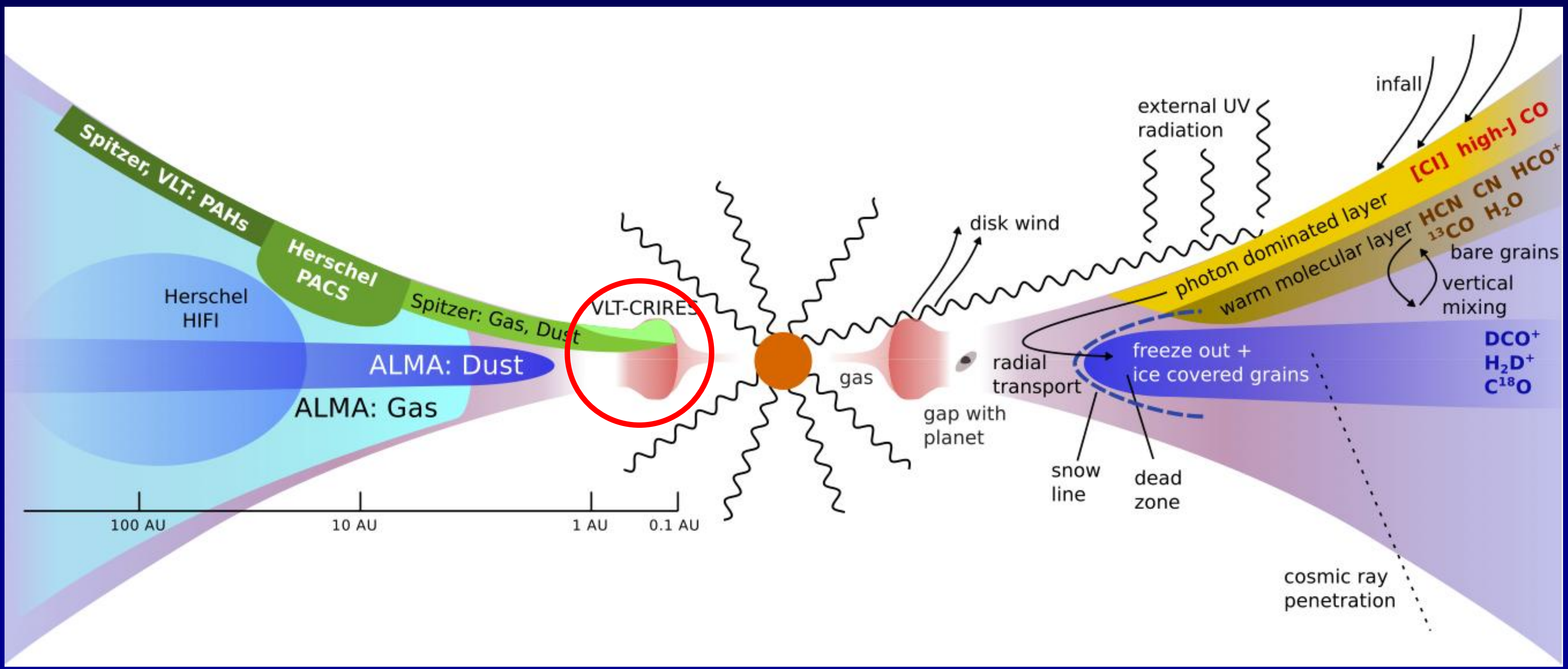


Carr & Najita 08
Salyk + 08



Lahuis +06

IR inner disk, mm outer disk

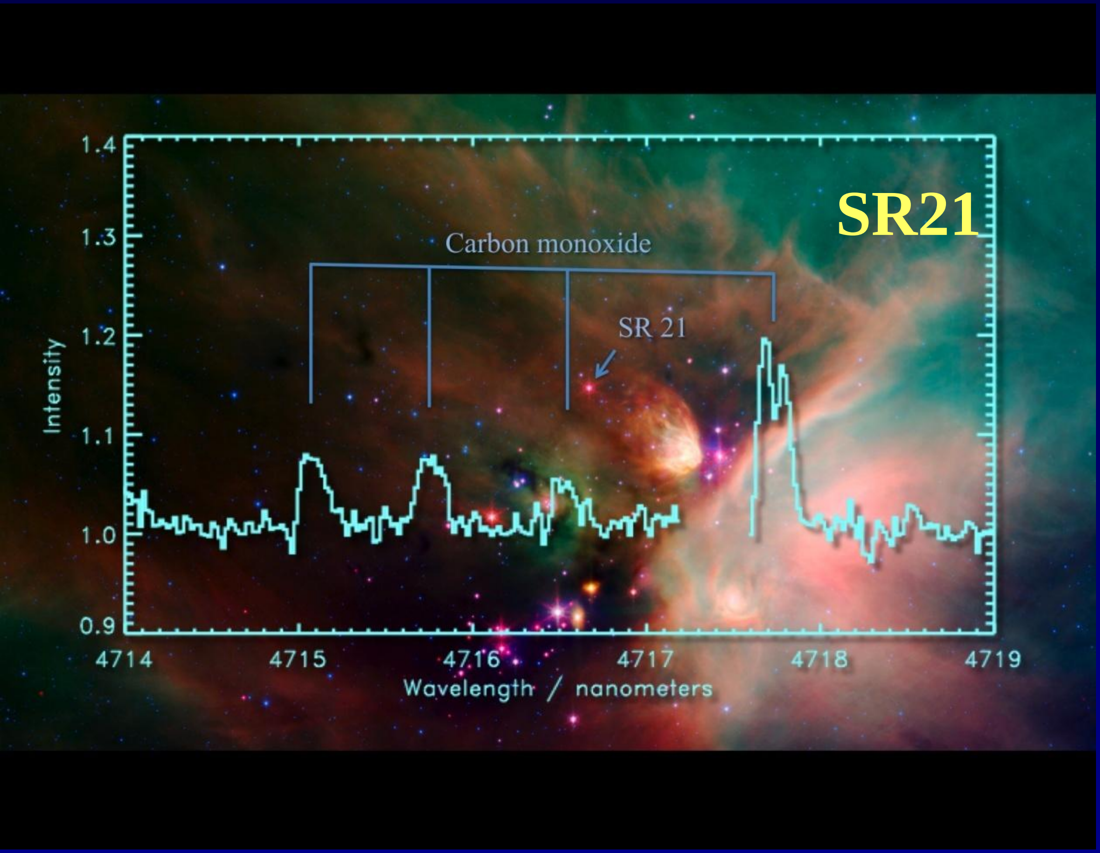


- VLT-CRIRES large program to survey CO and other species in inner AU

-70 T Tau stars, ~15 embedded sources

Pontoppidan+11, Herczeg+11, Bast+11, Brown+12

Evidence for disk + slow wind

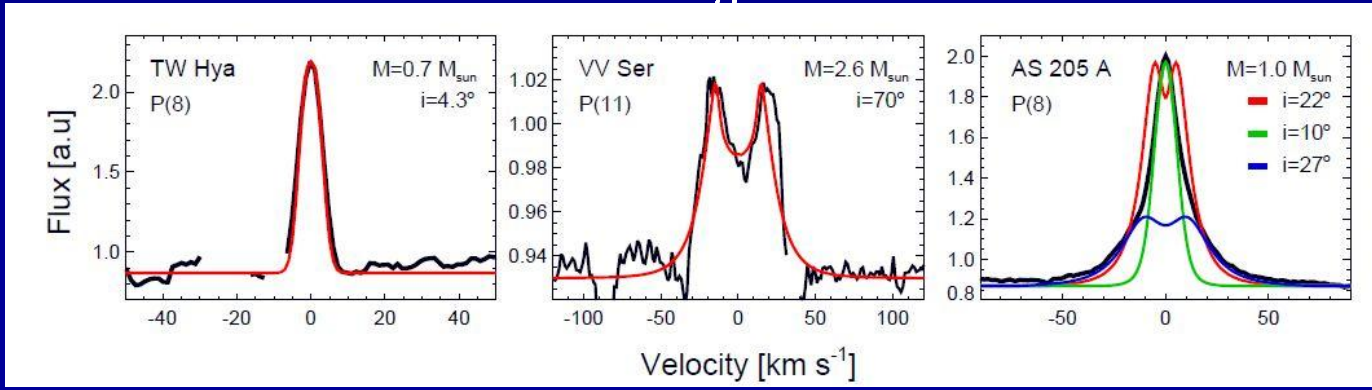


Pontoppidan +08

Face-on disk

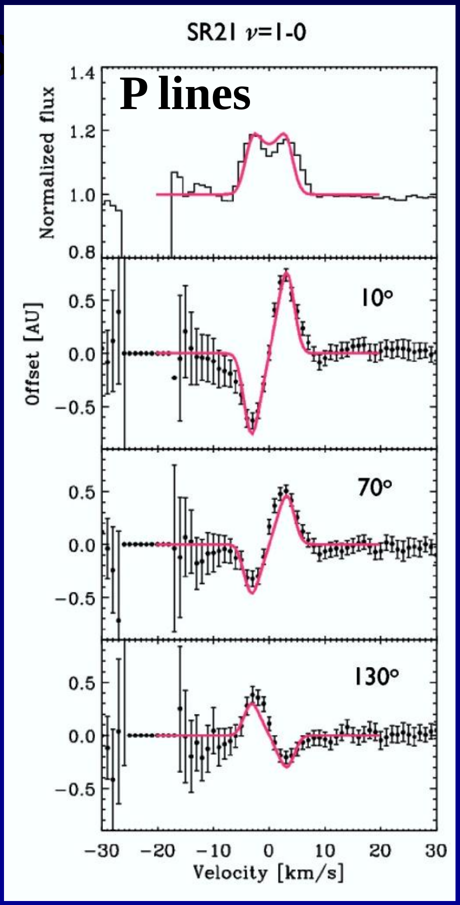
Edge-on disk

Disk + wind



Bast+11

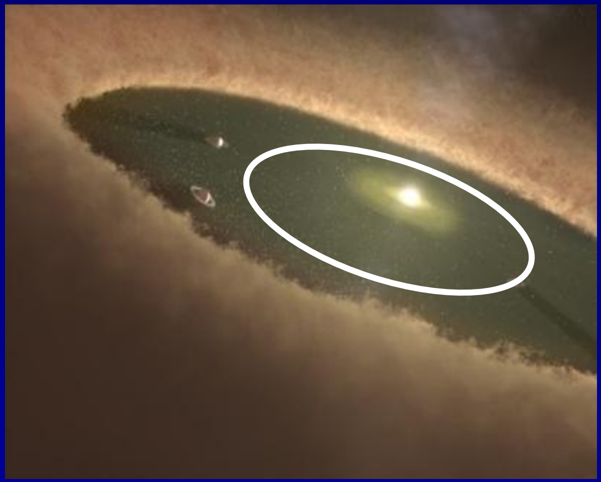
Locating CO in disks with SA



Pontoppidan+08

- Spectro-astrometry accuracy down to 0.1 AU rms (~200 μarcsec, comparable or better than VLTI and with high spectral resolution!)

Ring of gas at 7 AU

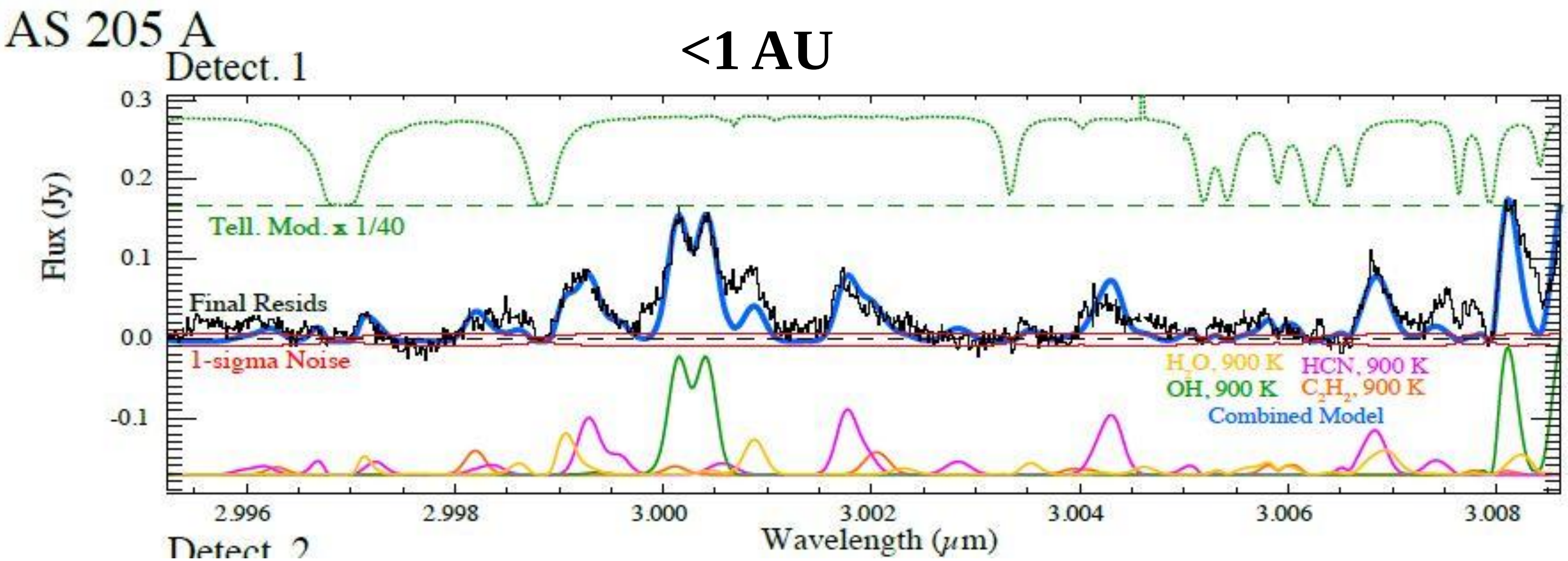


Gas present *inside* dust hole (20 AU radius)

Witnessing planet formation in action?

First near-IR detection of organics

<1 AU



Mandell +12, Bast+12

- **OH, H_2O detected in several sources**
- **HCN and C_2H_2 detected for first time at NIR**
- **CH_4 and NH_3 not convincingly found**
- **Chemistry consistent with high-T reactions, not ice evaporation**

Conclusions

- **Remarkable developments in astrochemistry over past 30+ years**
  - **From clouds to planet-forming zones of disks**
  - **Gas phase → gas-grain chemistry**
- **Progress driven by new instrumentation at high spectral and spatial resolution**
- **Enormous potential for ALMA, e-ELT**

Thanks ESO!

www.eso.org