Water in the Universe

Ewine F. van Dishoeck

Leiden Observatory / Max-Planck Inst. für Extraterrestrische Physik

With thanks to many colleagues, i.p. WISH team

See Euronews space magazine

Serpens core, IR image 2’x2’ VLT-Hawk-I

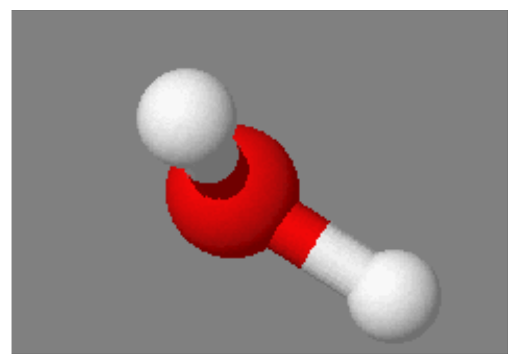
Outline

- **Why water?**
- **How to observe water**
- **Water puzzles**
  - **External galaxies**
  - **Evolved stars**
  - **Shocks**
  - **Diffuse + translucent clouds**
  - **Molecular clouds, pre-stellar cores**
  - **YSOs**
  - **Disks: outer vs. inner disks**
  - **Comets and the solar system**

See Cernicharo & Crovisier 2005, Bergin & Melnick 2005, Th. Encrenaz 2008 ARA&A for recent reviews

Why interest in water?

- A dominant form of oxygen => affects all species
  - Oxygen budget puzzle
- Diagnostic for 'hot spots'
  - Large variation H_2O gas abundance $<10^{-8}$ to 3.10^{-4}
- Role in energy balance as coolant
  - Heating agent if IR pumped
- Origin of water on Earth (through HDO/H_2O)
  - Water trail from clouds ⍰ disks ⍰ comets, planets
- Chemistry of life occurs in water



Oxygen budget in a cold dense cloud

Component	Fraction of solar O	Observations
Refractory dust	30%	Optical/UV, IR
Ices (H_2O,CO_2, CO)	26%	Mid-IR
Gas-phase CO	9%	Submm Mid-IR
Remainder (O? O_2? H_2O?)	35%	Far-IR, Submm, Mid-IR

Taurus cloud

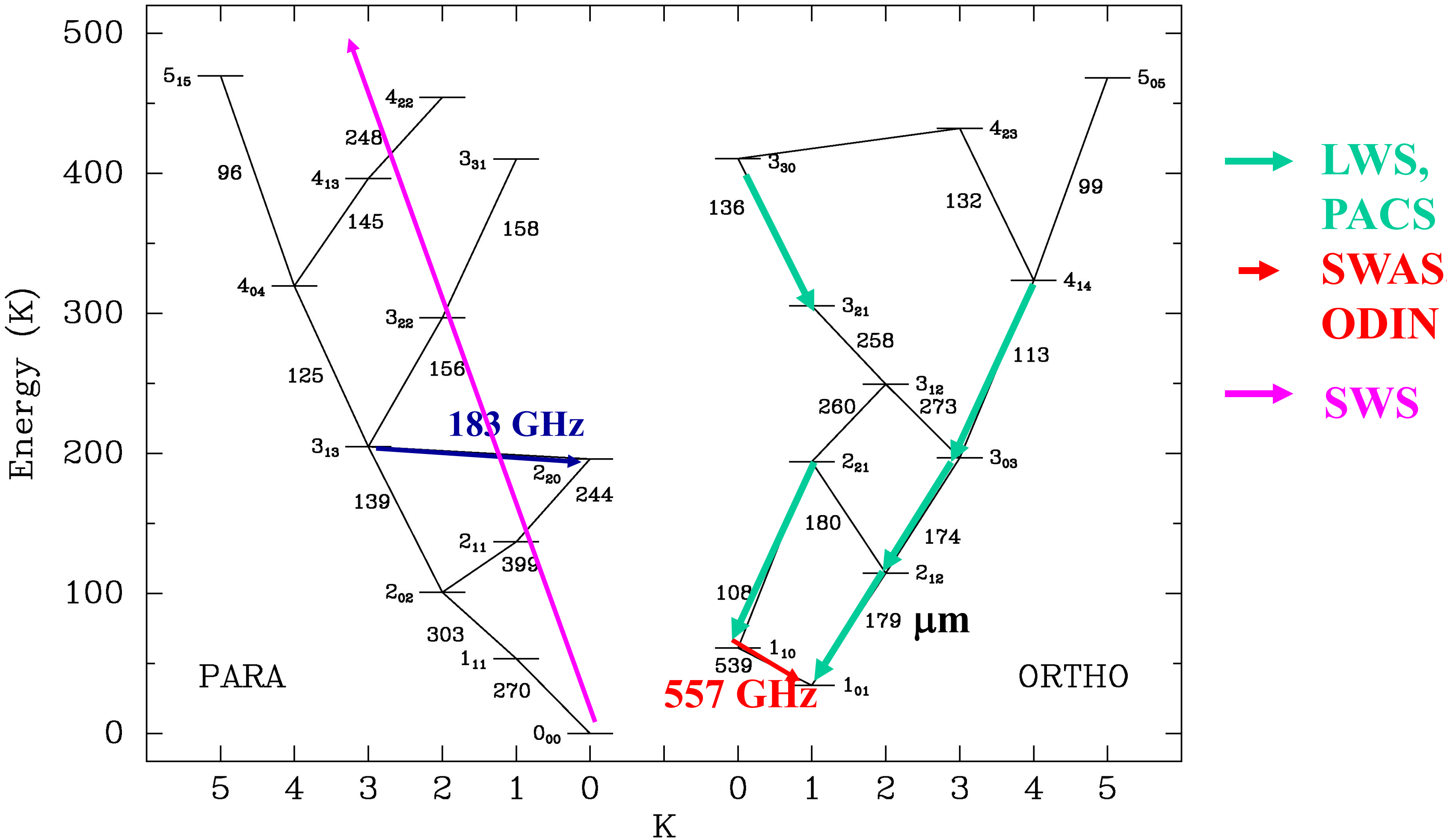
Q: where is missing oxygen?

Whittet et al. 2007

Further motivation

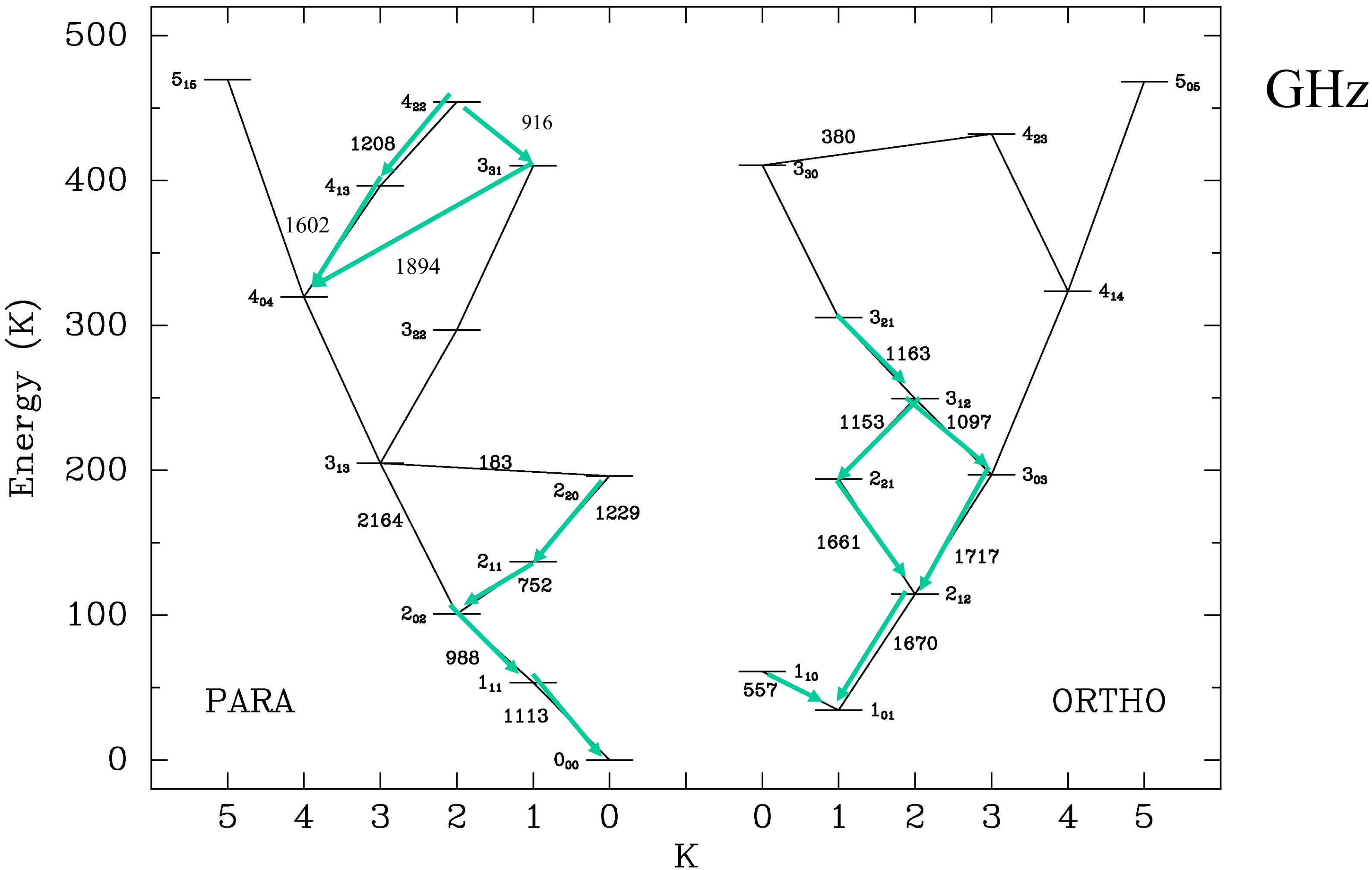
- **Traces basic ice formation and desorption: test of gas-grain chemistry**
- **H_2O as a dynamical probe of warm high density gas: infall, outflow, quiescent gas, mixing, …**
- **H_2O as a radiative transfer challenge: high/low optical depths, masers, ….**

H_2O transitions (μm)



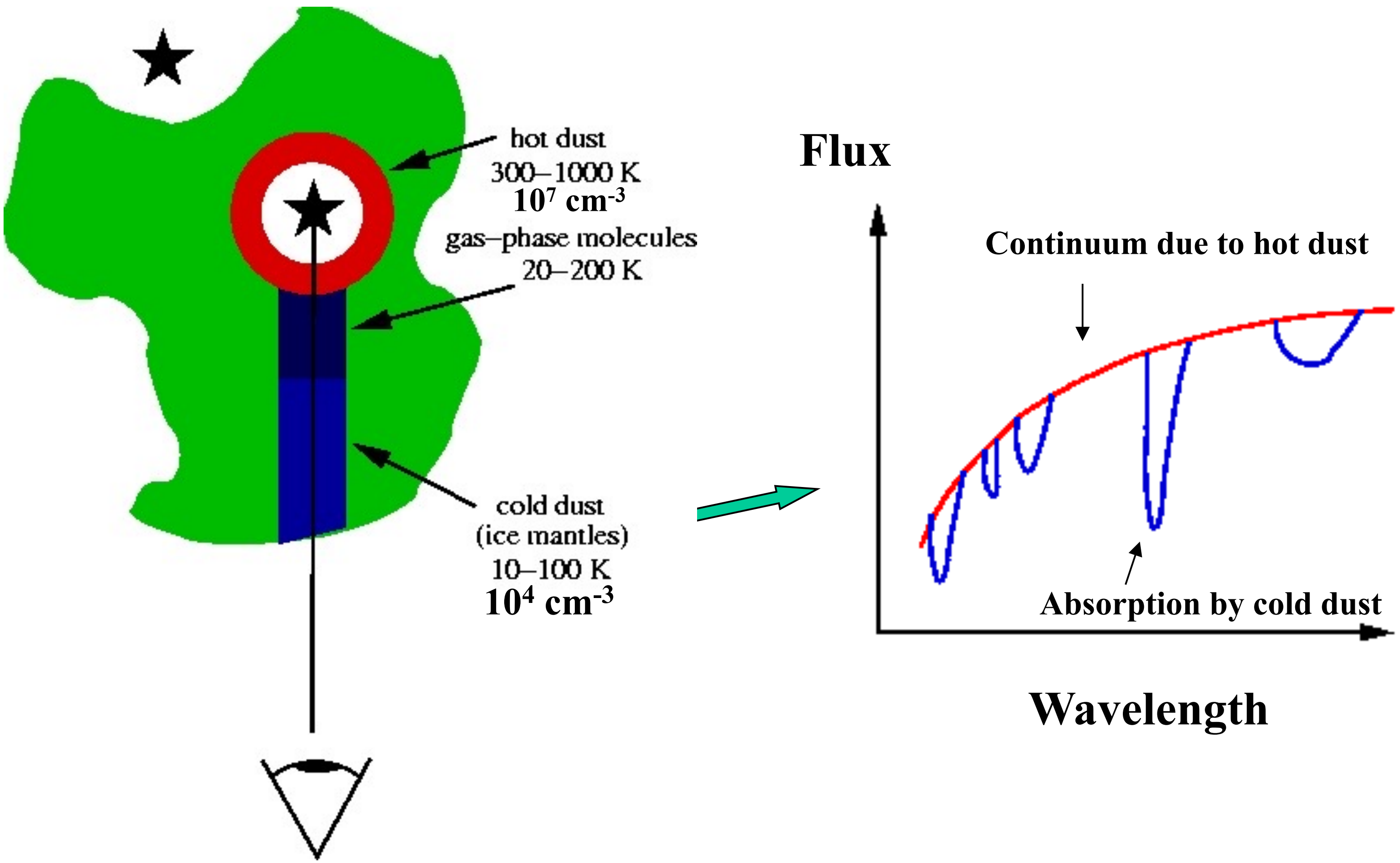
- Also 22 GHz maser, first detected in Orion by Cheung et al. 1969

H_2O Herschel-HIFI lines



Lines with range of excitation conditions available, with orders of magnitude better sensitivity, spatial and spectral resolution

Infrared: absorption gas and solids



Vibrational transitions of H_2O gas *and* ice

Long wavelength FIR transitions in emission

H_2O gas chemistry

- **Cold ion-molecule chemistry:**
  - **$O + H_3^+$? OH^+ ?… ? H_3O^+ + e ? H_2O**

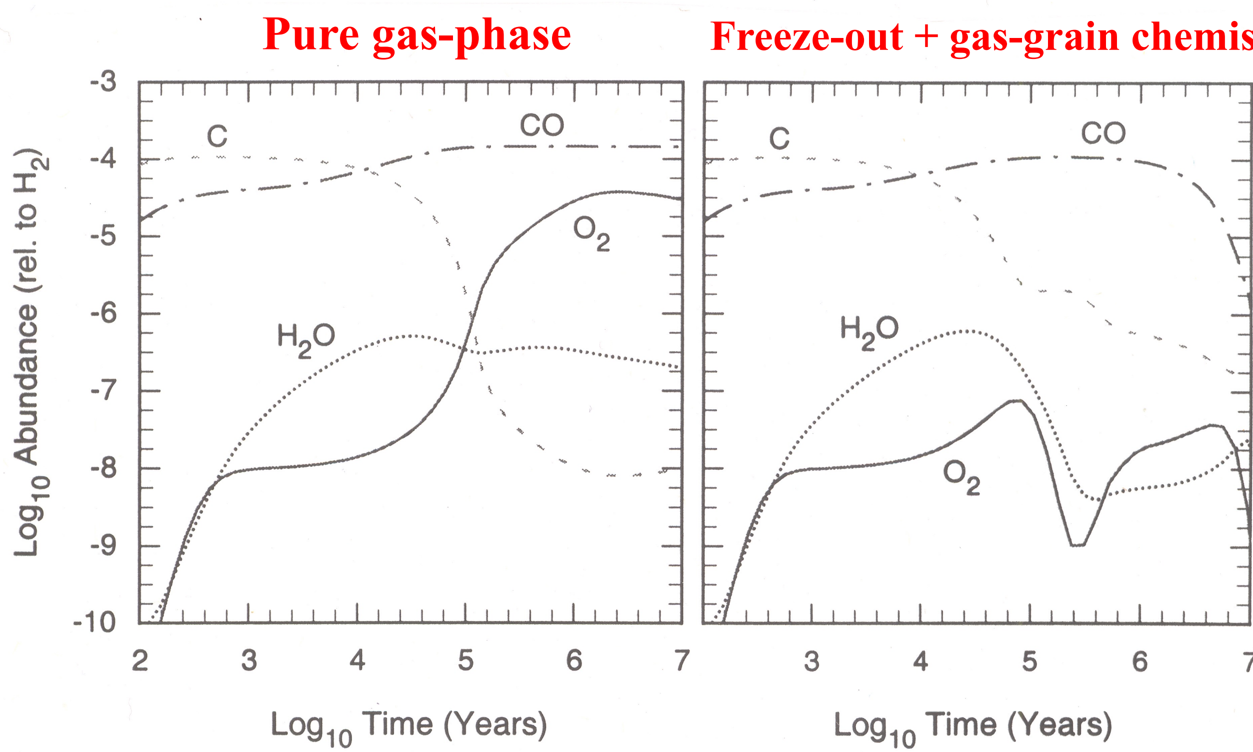
    Typical abundances ~10^{-7}
- **High-temperature chemistry (>230 K):**
  - **$O + H_2$? OH ? H_2O**

    Drives all gas-phase O into H_2O => abundance >10^{-4}

    Back reactions with H drive H_2O back to OH and O
- **Photodissociation by UV radiation:**
  - **H_2O ? OH + H**

Rates for most/all (?) reactions well known

Oxygen chemistry



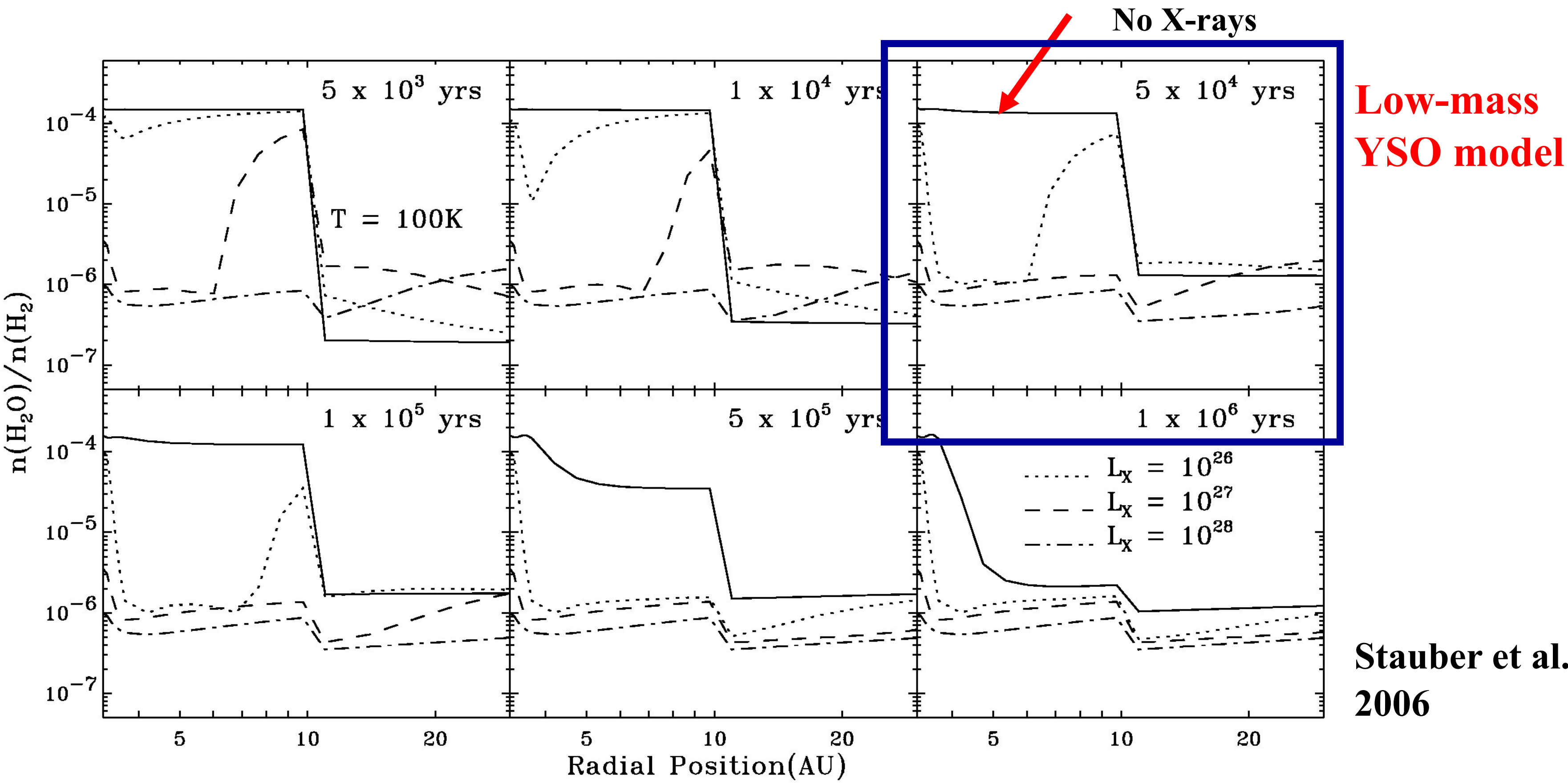
O → H_2O^{gr} → sticks

C → CH_4^{gr} → evaporates

Bergin et al. 2000

- **Pure gas phase chemistry at low *T* produces H_2O abundance of ~10^{-7}, and eventually drives all O into O_2**

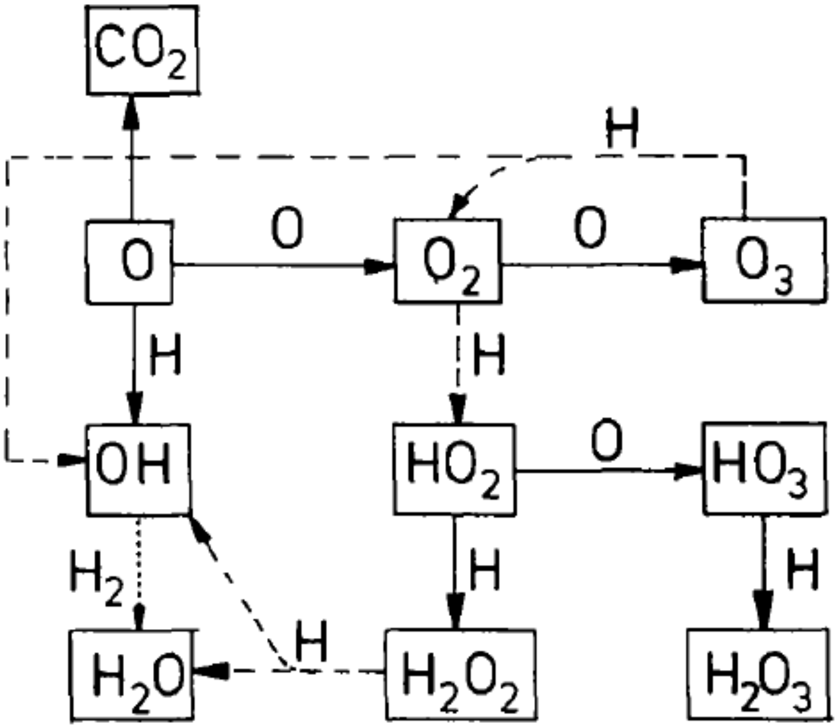
X-ray destruction of water



- H_2O destroyed close to X-ray source in $5x10^4$ yr for $L_X= 10^{27}$ erg s^{-1}
  - H_3^+ and He^+ more abundant
  - UV from secondary electrons with H_2
- Faster destruction for higher fluxes

H_2O grain chemistry

- Three routes for producing H_2O, through hydrogenation of O. O_2 and O_3
  - Relative importance depends on rates, energy barriers, hopping, diffusion, …
- Postulated >25 yr ago, only now being tested in laboratory
  - Miyauchi et al. 2008, Ioppolo et al. 2008
- Desorption mechanisms
  - Thermal desorption: Fraser et al.
  - Photodesorption: Öberg et al.
  - CR-induced desorption

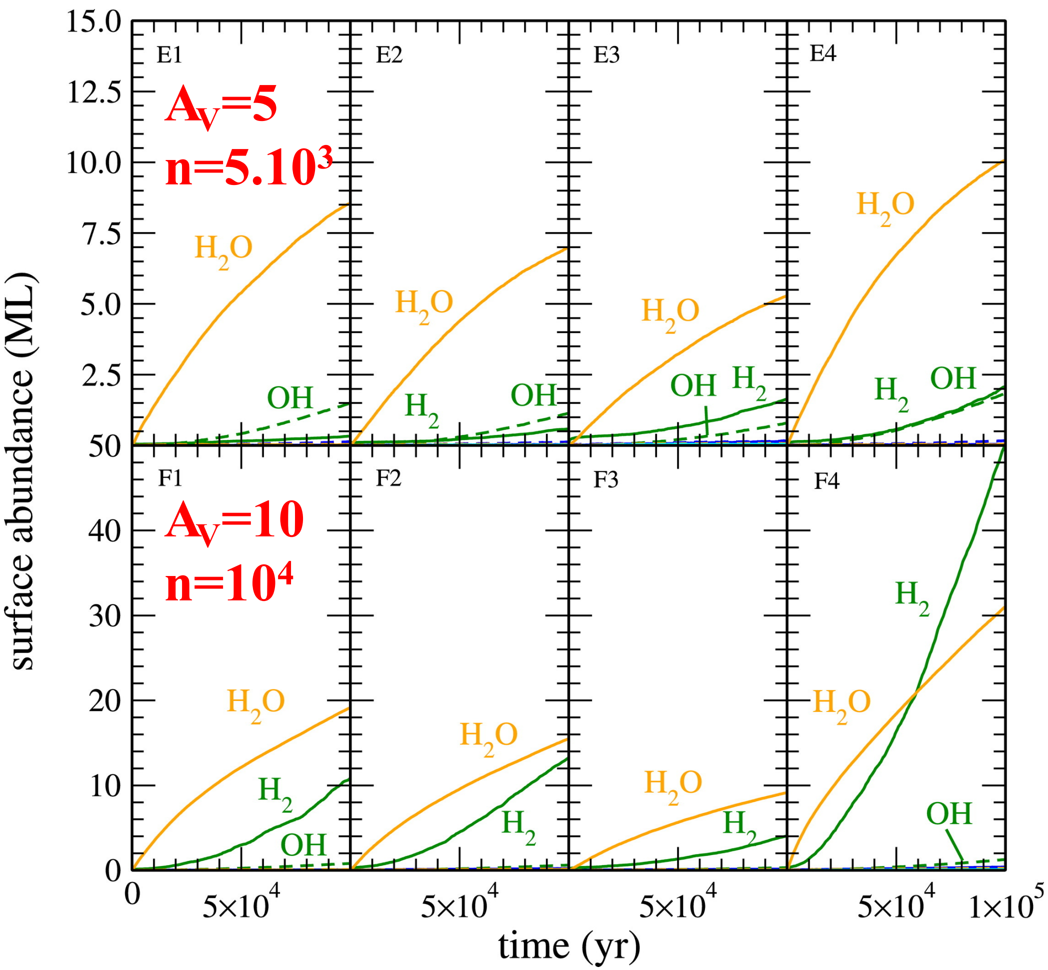


Tielens & Hagen 1982

Q: can this model be tested observationally?

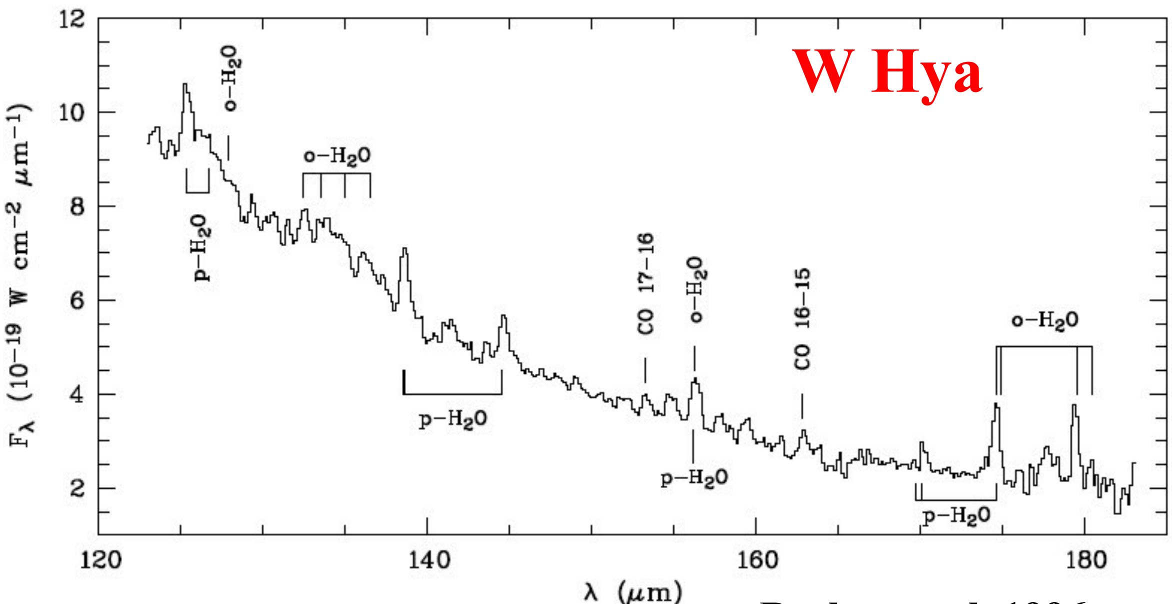
Water ice formation

- **Formation several monolayers of H_2O and OH ice in translucent clouds**
- **Form thick ice layers in dense clouds**
- **Results depend sensitively on molecular data, grain morphology, …**
- **Underproduce H_2O ice compared with observations**

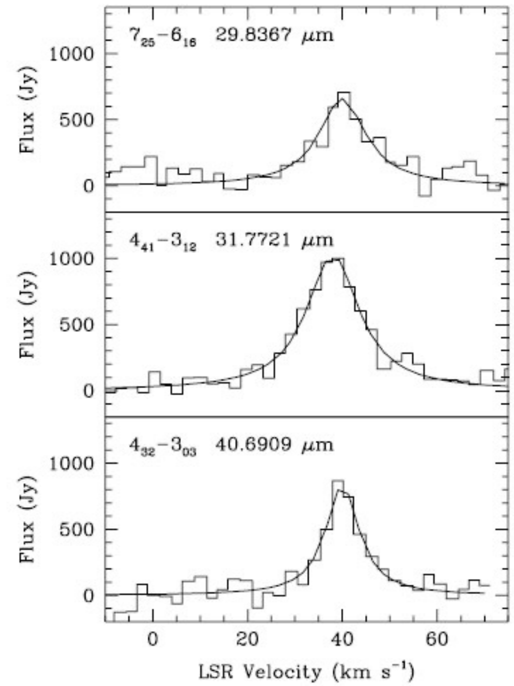


Cuppen & Herbst 2007

Water in O-rich evolved stars



Barlow et al. 1996



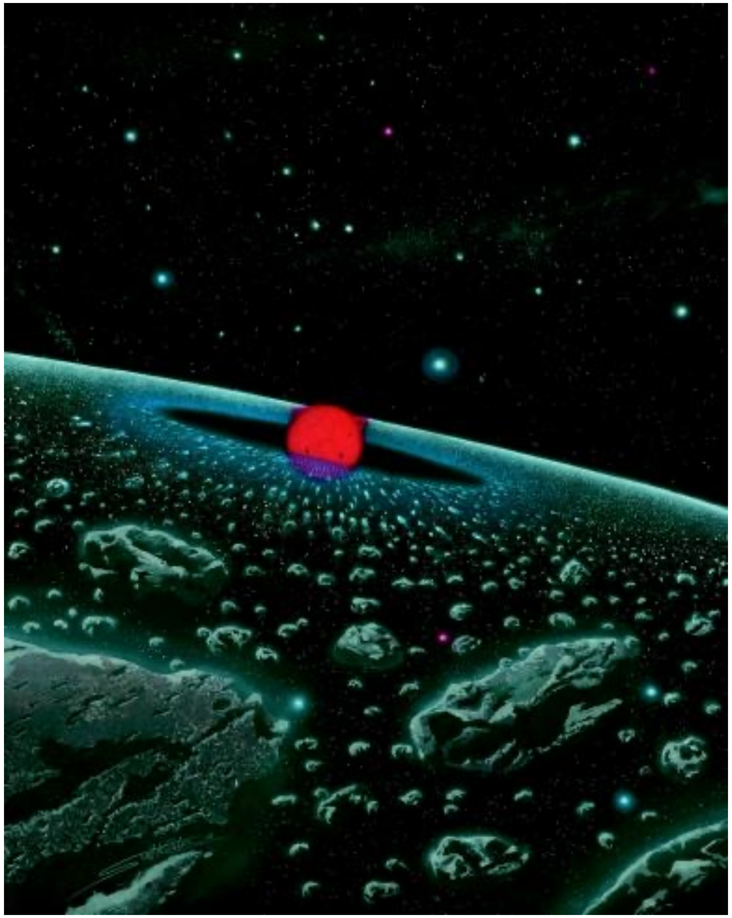
Neufeld et al. 1996

- **Major coolant of outflowing circumstellar gas**
- **Many lines detected by ISO-LWS and SWS**
- **Major differences in inferred *dM/dt* by different groups, related to different gas temperature structures?**

Q: what does H_2O tell us about physical structure ?

Water in C-rich evolved stars

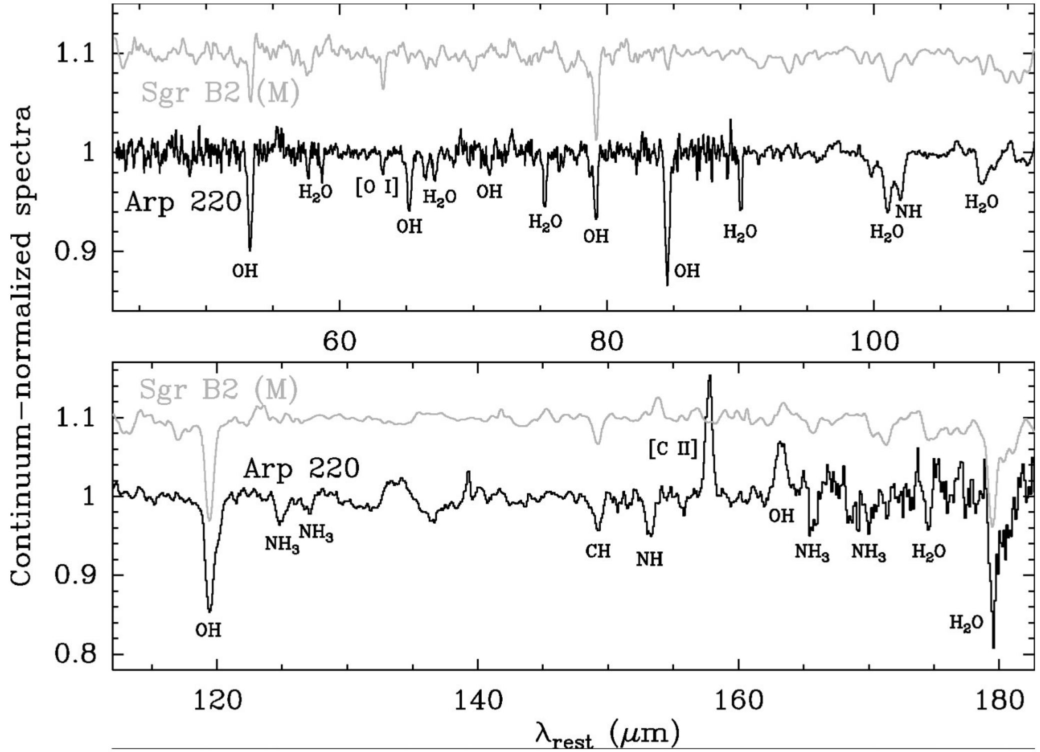
- **Detection of H_2O in C-rich envelope IRC+10216 came as a surprise**
- **Evaporating icy planetesimals?**



Melnick et al. 2001

Q: Origin O-rich species in C-rich stars? How common?

Water in external galaxies



Arp 220
ISO-LWS

Gonzalez-Alfonso et al. 2004

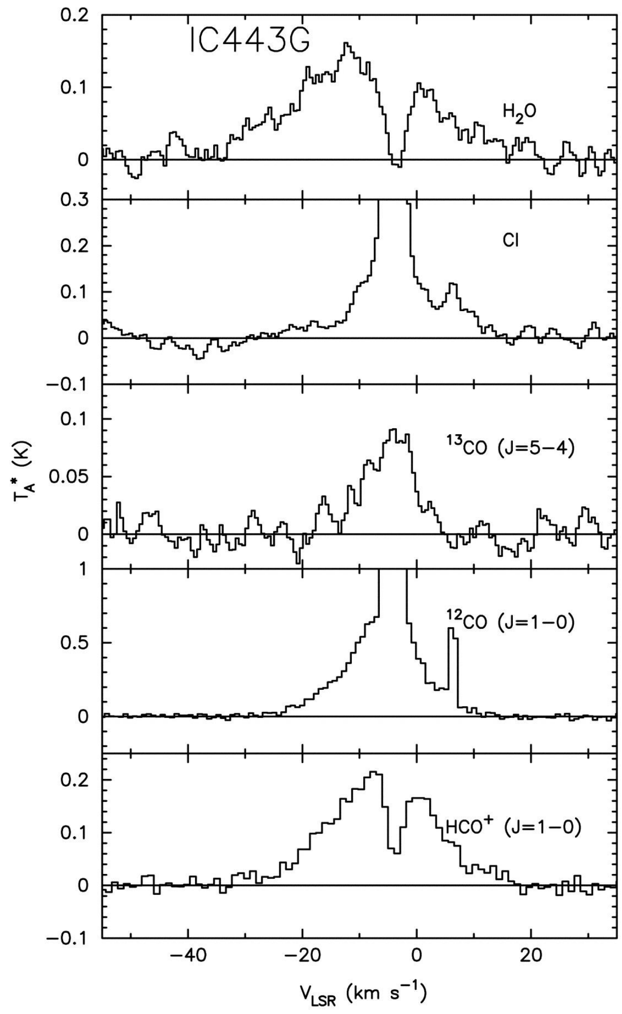
- **H_2O 22 GHz megamasers; trace black hole mass; 183 GHz Arp 220**
- **$H_2O/OH \sim 1$ in nucleus, ~0.1 in extended region from ISO-FIR absorption**
  - **Gonzalez-Alfonso et al. 2004, 2008, Goicoechea et al. 2005**
- **$H_2O/H_2 < 10^{-8}$ from ODIN on kpc scale; increases to 10^{-7} if 10% filling factor**
  - **Wilson et al. 2007**
- **H_3O^+ detected ⇒ $H_2O/H_2 \sim 2.\ 10^{-7}$ on few hundred pc van der Tak et al. 2007**

Q: Are these abundances characteristic of general ISM?

Shocks

- H_2O clearly detected in shocks associated with supernova remnants and YSOs
- Abundance ~10^{-7}-10^{-6} $\Rightarrow$ not all O driven into H_2O, except in densest regions and highest velocities
- UV photodissociation of pre-shock and shocked gas? Freeze-out behind shock? Shock physics?

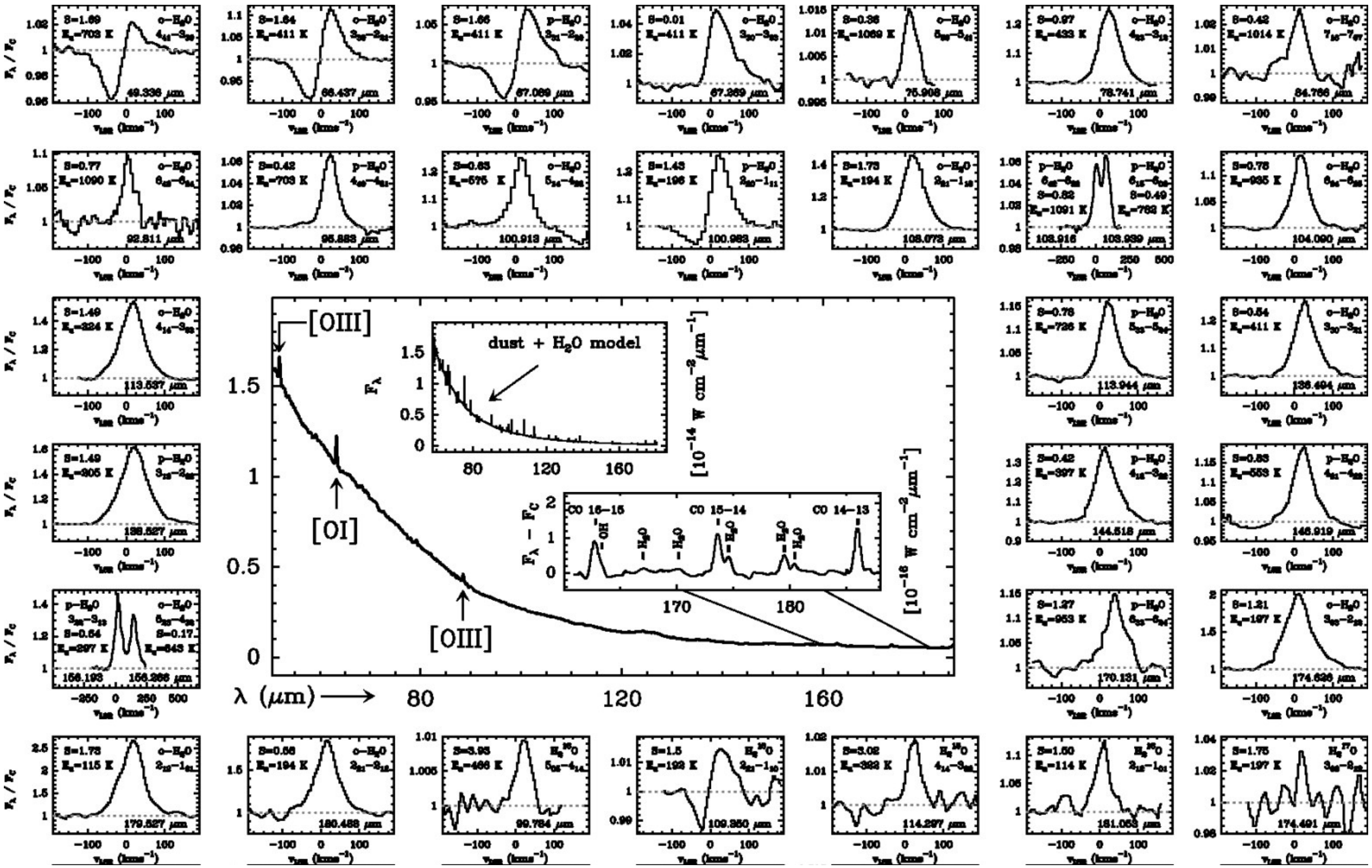
Supernova remnant IC443



Snell et al, 2005; Franklin et al. 2008

Q: why not all oxygen driven into H_2O at high T?

Orion outflow

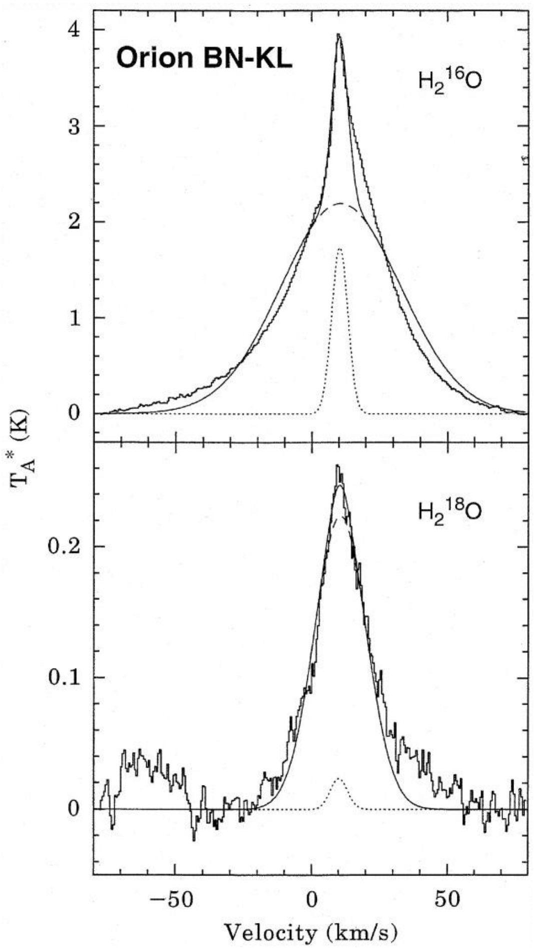


Cernicharo et al. 2006
Wright et al. 2000
Harwit et al. 1998

- Wealth of ISO-LWS and SWS lines, including absorption and P-Cygni profiles
- H_2O/H_2~$(2\text{-}3).10^{-5}$

Orion-KL H_2O and $H_2^{18}O$ profiles

Melnick et al. 2000, Olofsson et al. 2003



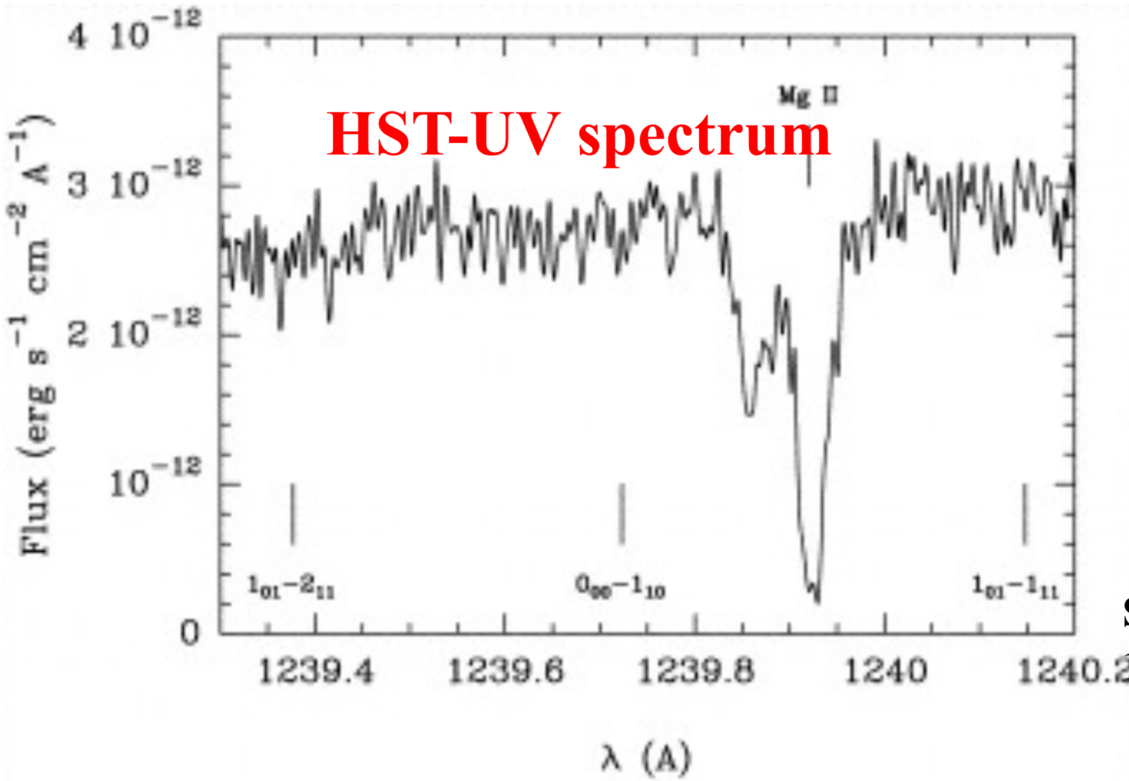
SWAS and ODIN observations:
Ground state 557 GHz
o-H_2O 1_{10}-1_{01}

Note broad line profiles, even for $H_2^{18}O$ => shock

Abundance ~10^{-4}
⇒Most O driven into H_2O

- **H_2O abundance in extended cloud may be as low as 10^{-8}, but still controversial**

Water in diffuse and translucent clouds



HD 154368

Spaans & Neufeld 1995

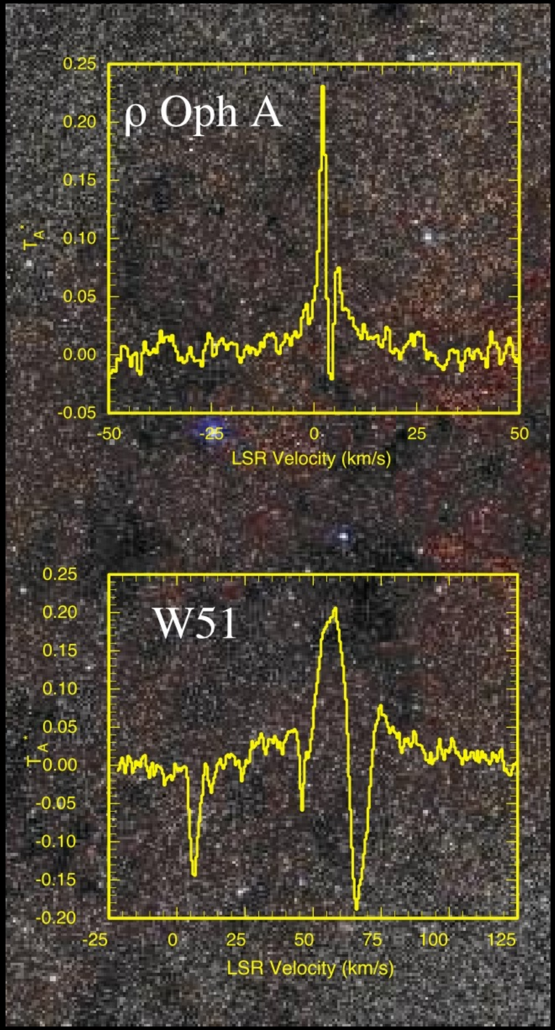
- $H_2O/H_2<10^{-8}$ from UV absorption
- $H_2O/H_2\sim10^{-8}$-few.10^{-7} from 557 GHz absorption
  - Neufeld et al. 2000, 2002; Plume et al. 2004
- $H_2O/H_2\sim3.10^{-7}$ from IR absorption toward Galactic Center
  - Moneti & Cernicharo 2000

Q: are results consistent with pure gas-phase chemistry?

General molecular clouds

o-H_2O 557 GHz
1_{10}-1_{01}

Snell et al. 2000
Wilson et al. 2003

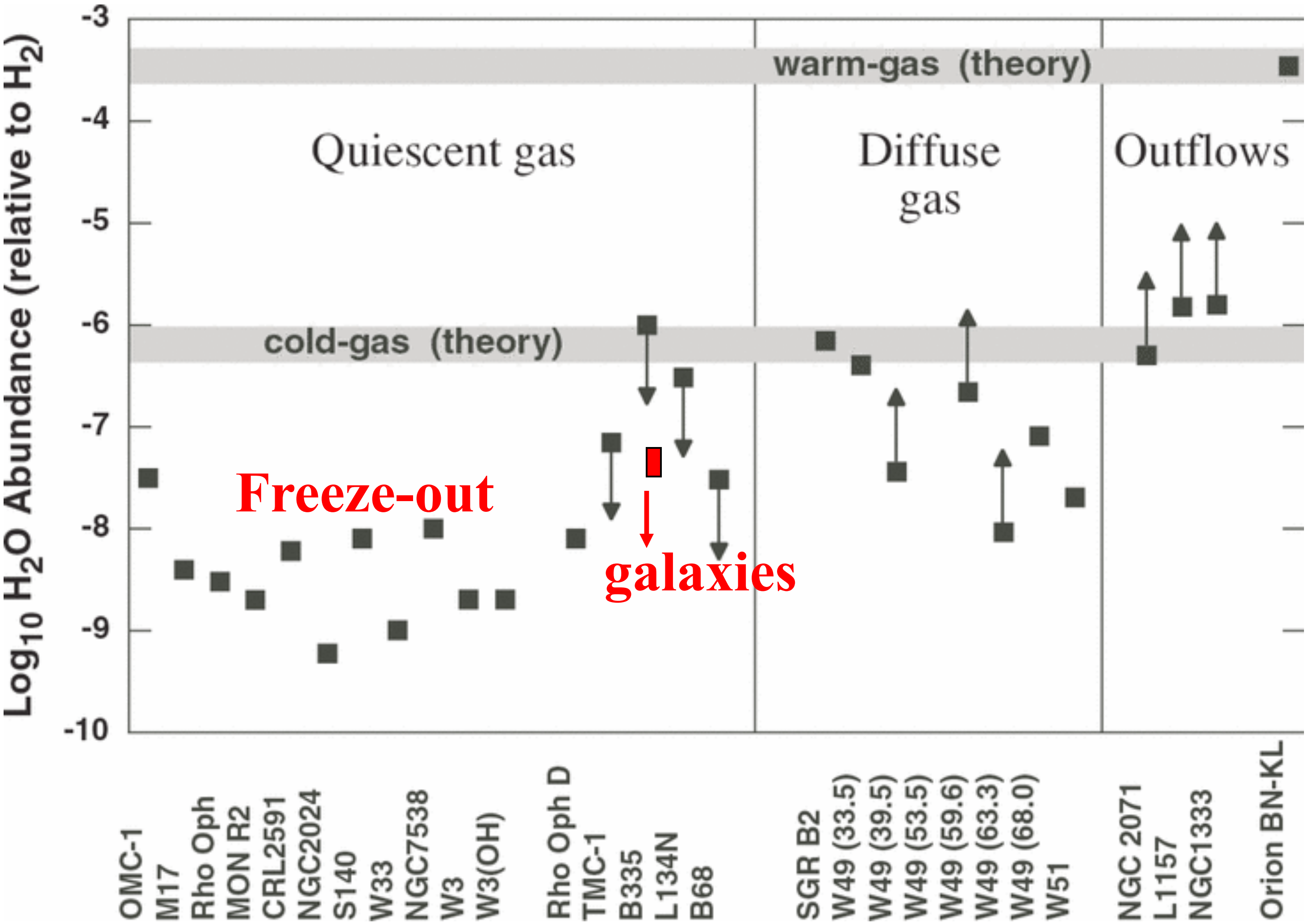


-SWAS and ODIN (~3'):

Water emission is weak =>
most water frozen out on
grains in cold clouds

Q: how low is water abundance in cold clouds?
is this consistent with ice abundances?

Summary (o-)H_2O abundances

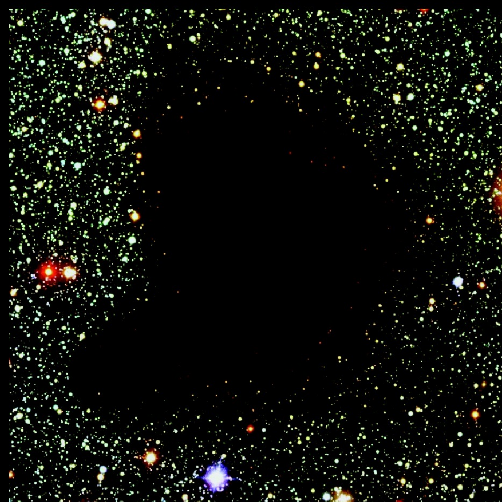


Bergin & Melnick 2005

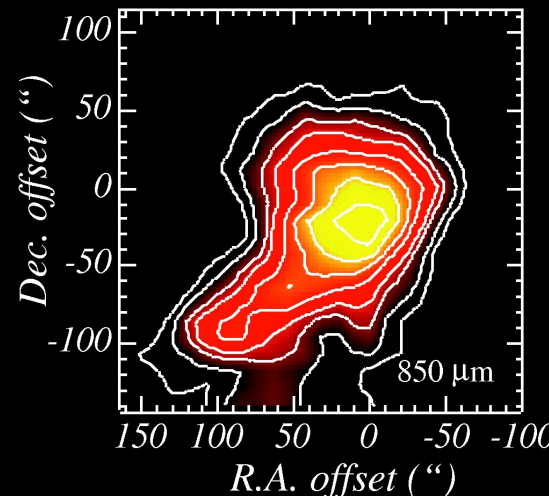
Low-Mass: Pre-stellar cores

B68

Optical

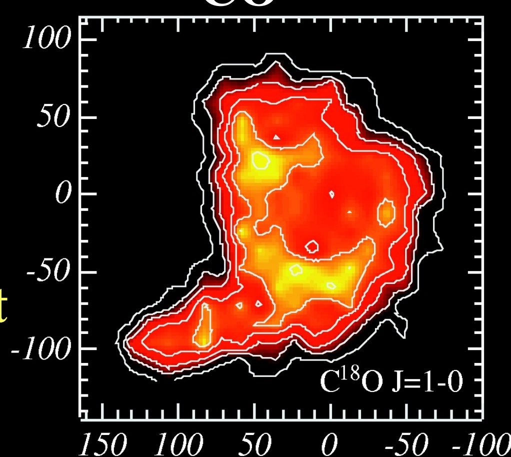


Submm continuum

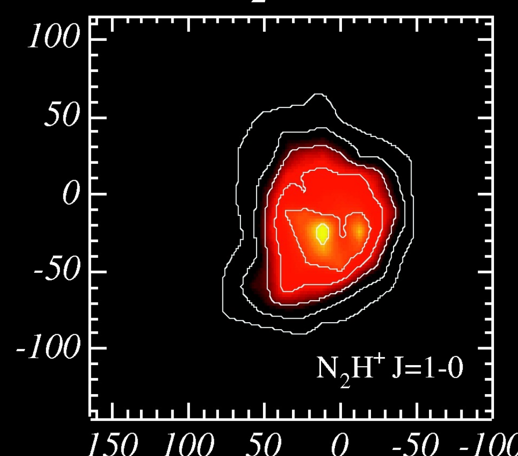


SWAS limit
=>o-H_2O <3.10^{-8}

CO



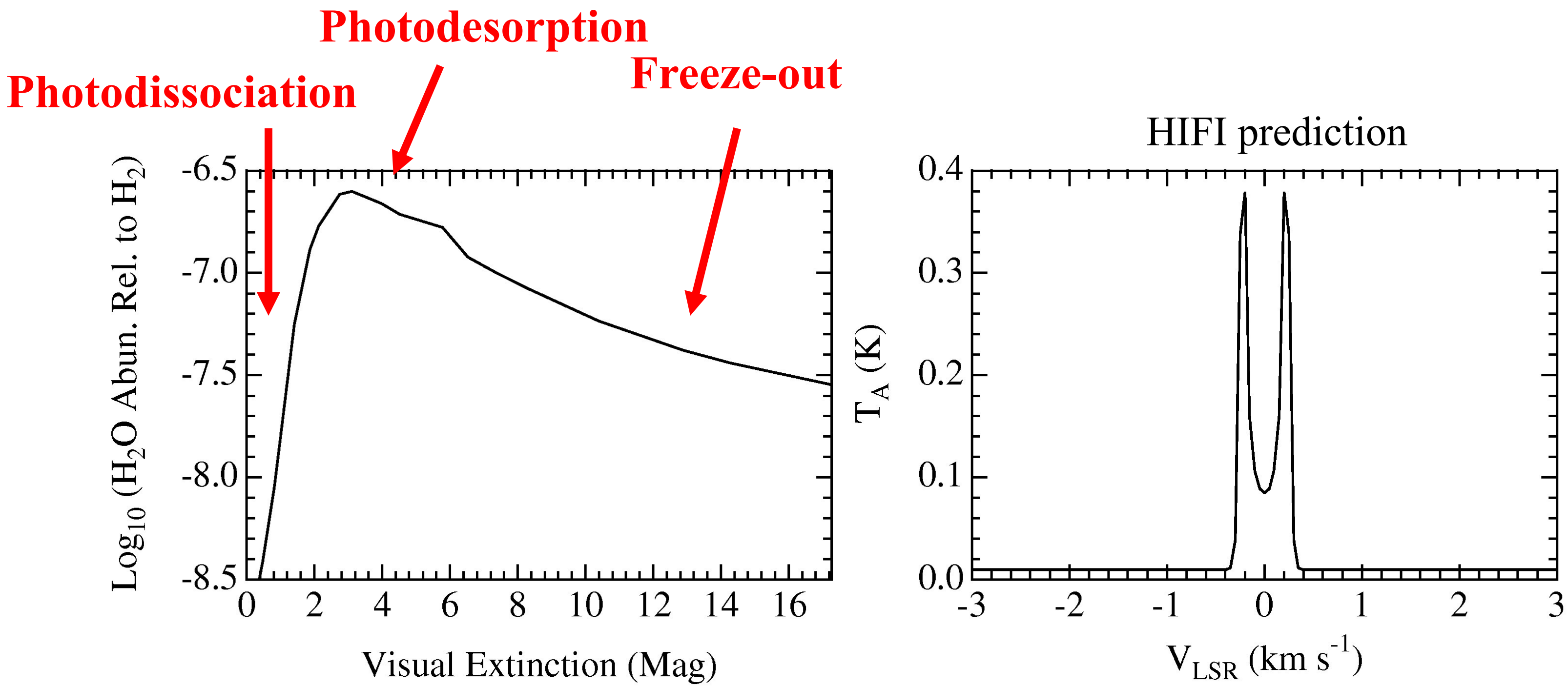
N_2H^+



CO avoids densest, coldest part of core

Bergin & Snell 2002

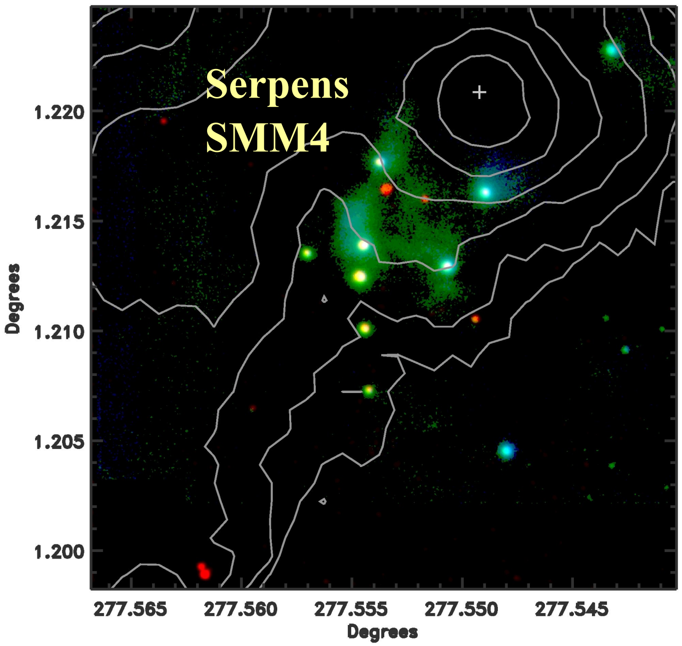
Model B68 water profile

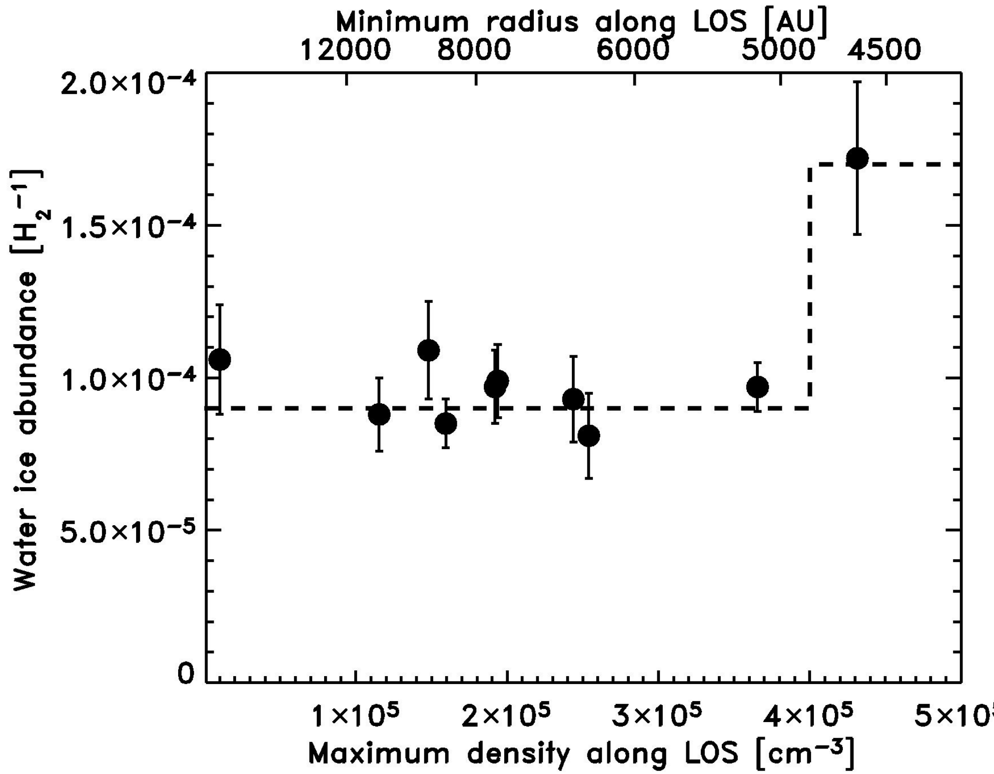


- *Q: Where does onset for H_2O ice formation and freeze-out occur?*
- *Q: How effective are non-thermal desorption mechanisms?*
- *Q: What is para-H_2O abundance?*

Hollenach et al. 2008

Ice abundances in cold clouds





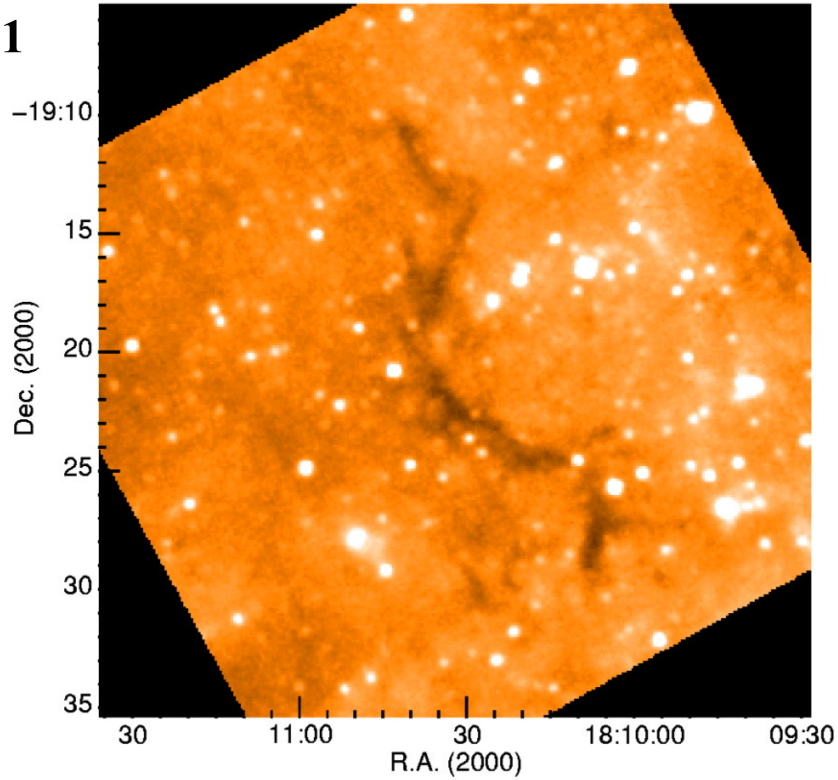
-Q: why is most, but not all, oxygen in ices? Atomic O?

Pontoppidan et al. 2004

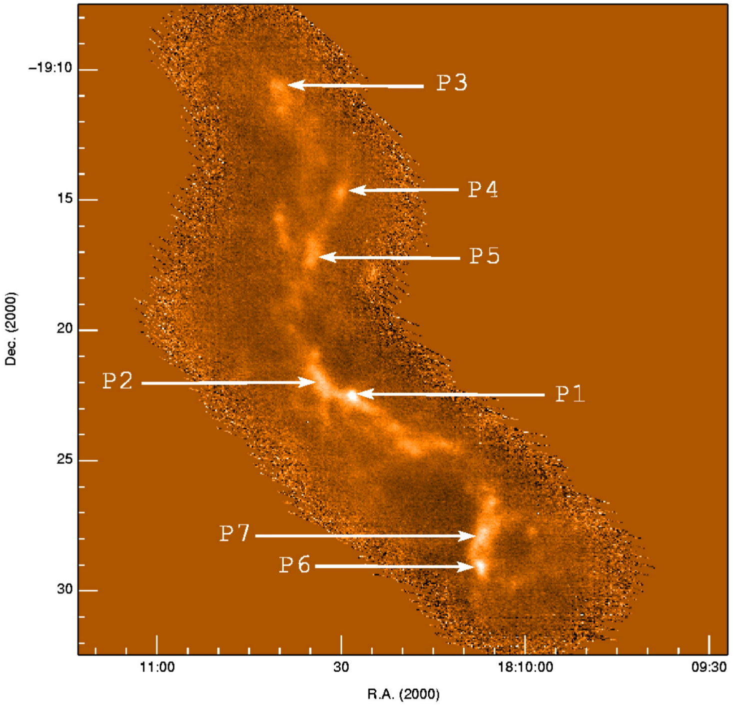
High-mass pre-stellar cores

G11.11

MSX



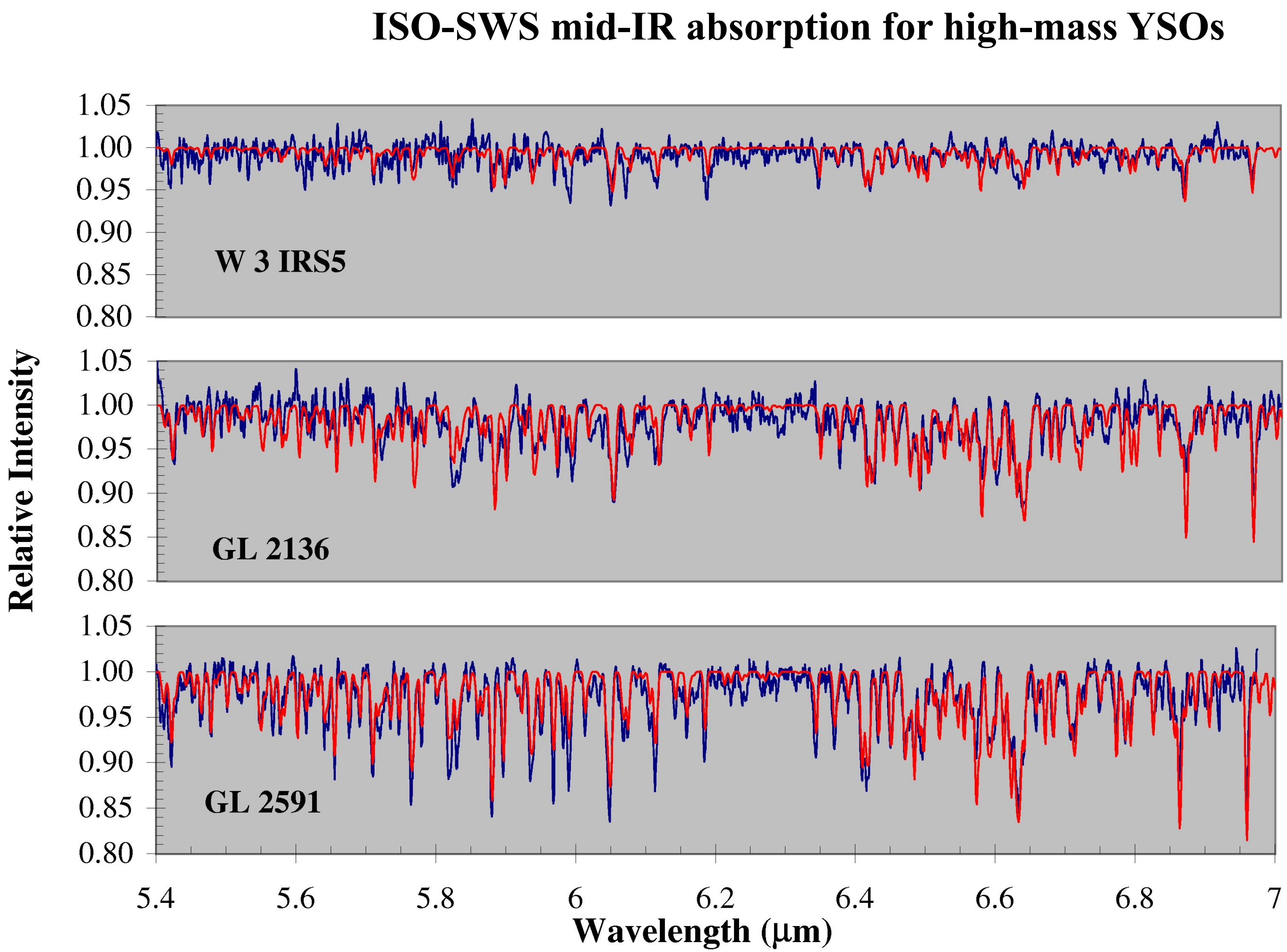
SCUBA



-Q: do high-mass pre-stellar cores have similarly low H_2O gas abundances?

Johnstone et al. 2003

Hot, steaming water near protostars



Blue=data

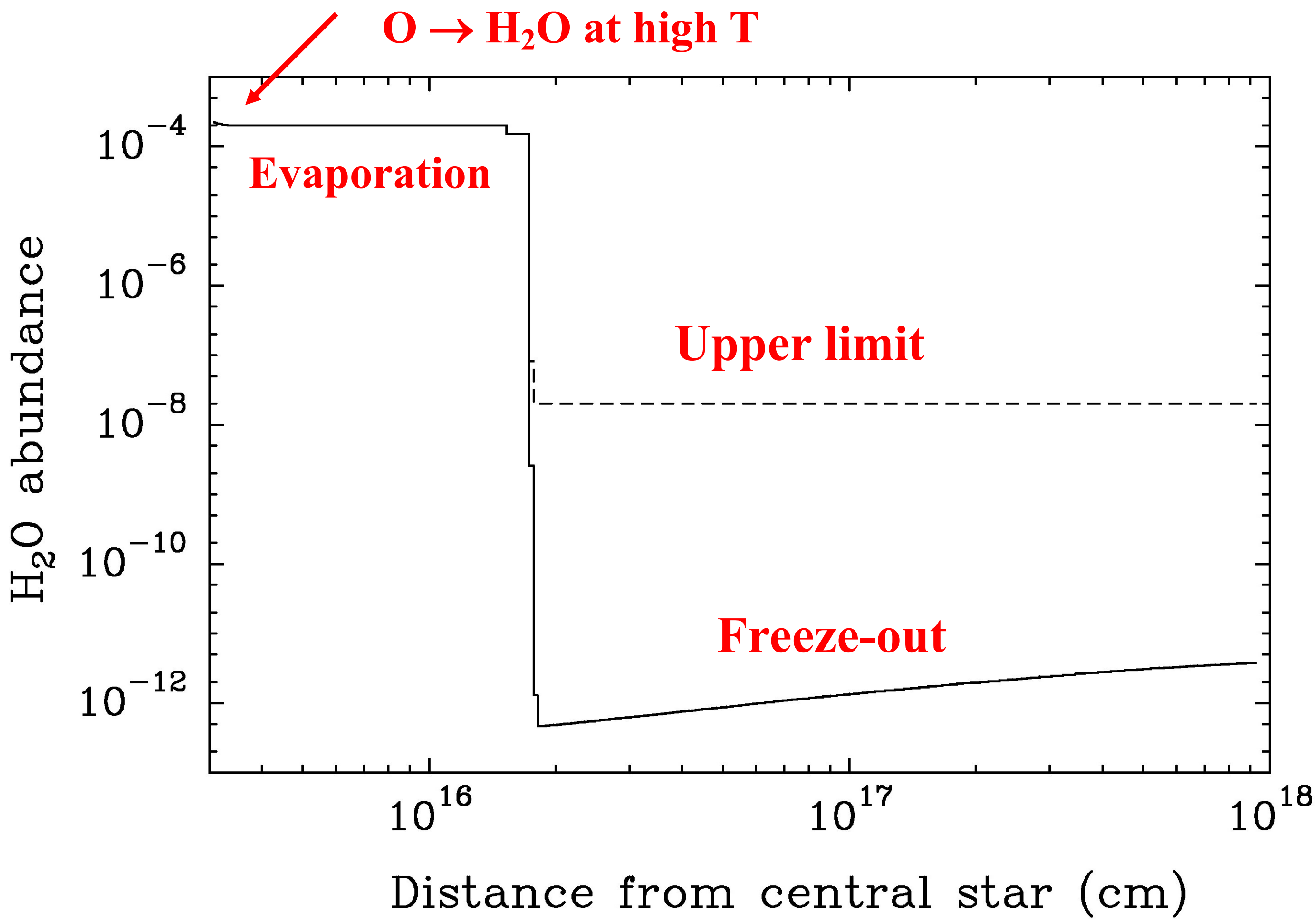
Red=model

T_{ex}=300 K

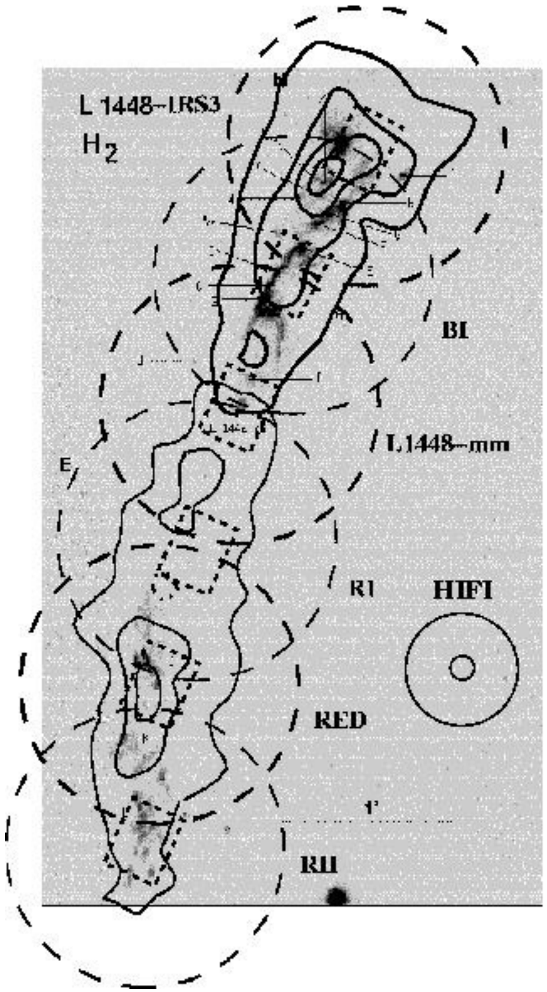
Combine with SWAS and ISO-LWS data to constrain abundance profile

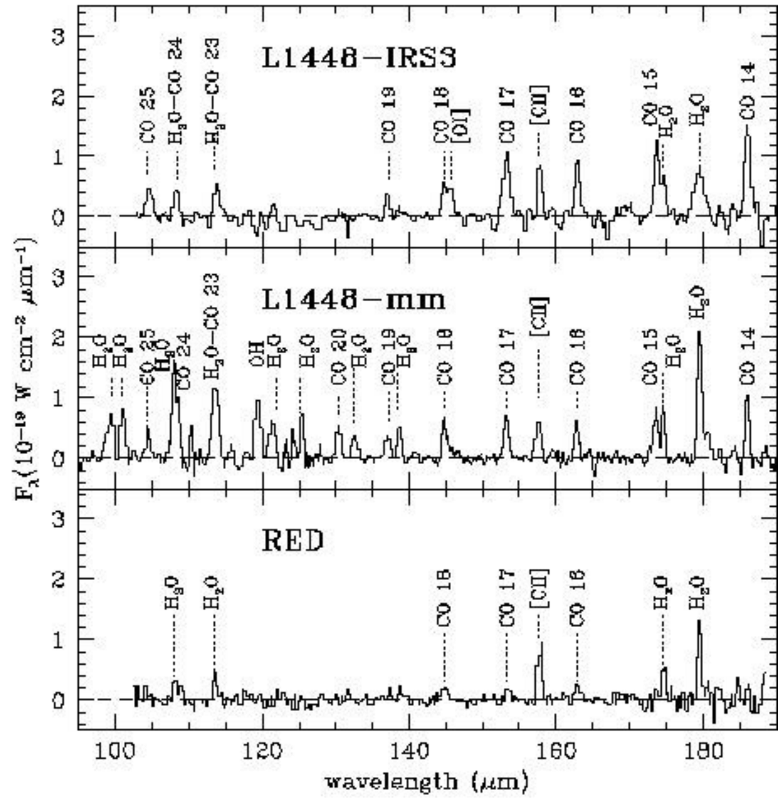
Helmich et al. 1996
Boonman et al. 2003

Inferred abundance profile



Low-Mass: Class 0 sources

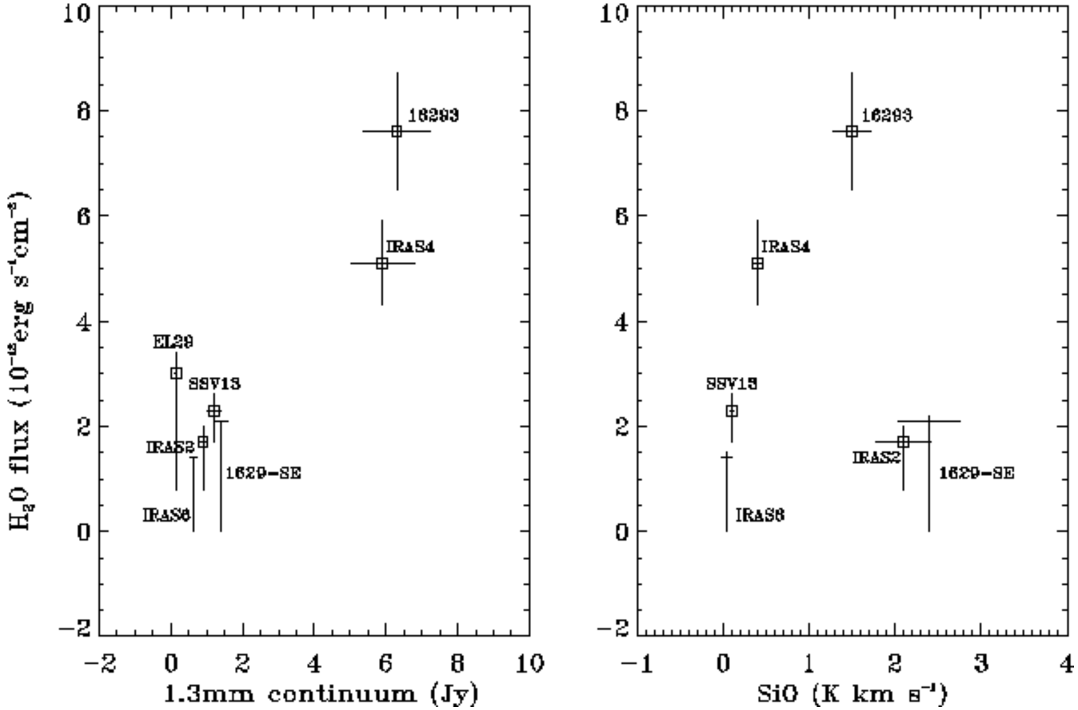




-Q: What is origin of strong H_2O emission?
Quiescent warm envelope or outflow?

Nisini et al. 1999, 2000
Ceccarelli et al. 1998

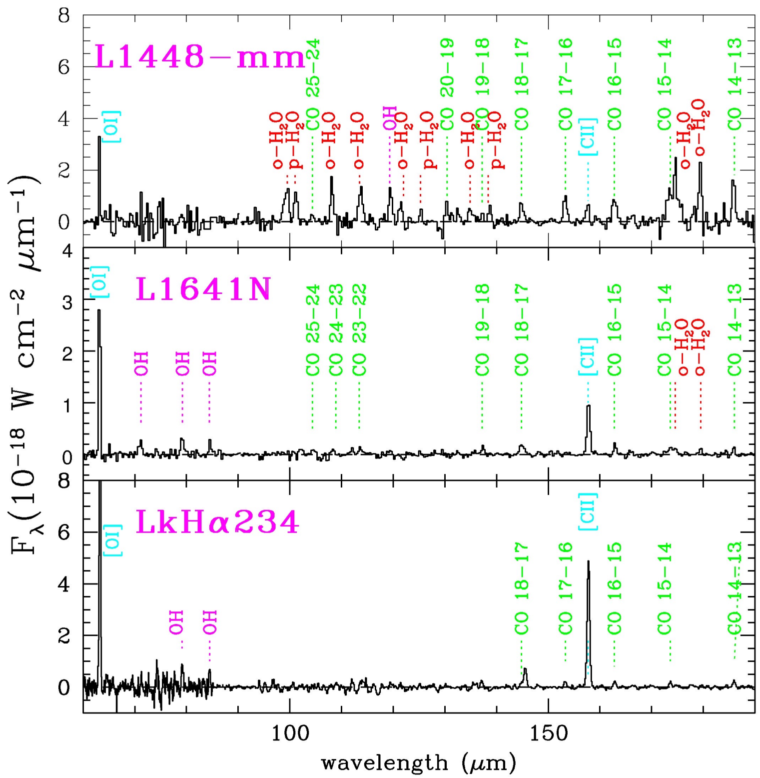
Try to link H_2O with mm continuum and SiO



- Q: Are these real correlations or not?

Ceccarelli et al. 1999

Low-Mass: Class I sources



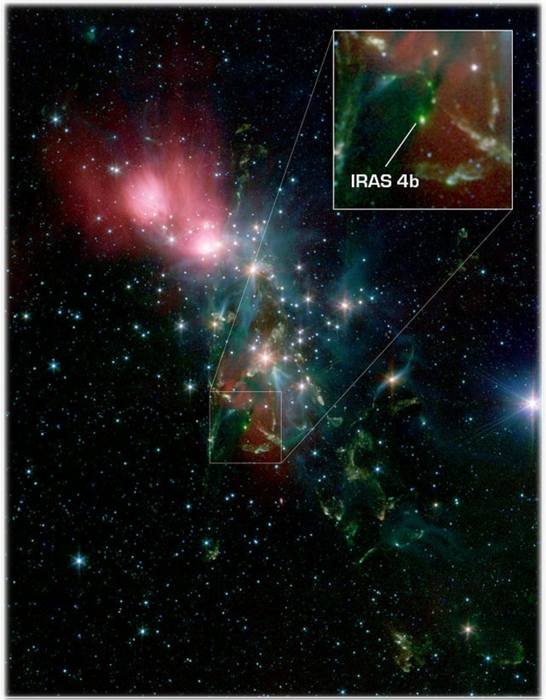
Class 0: H_2O

Class I: OH

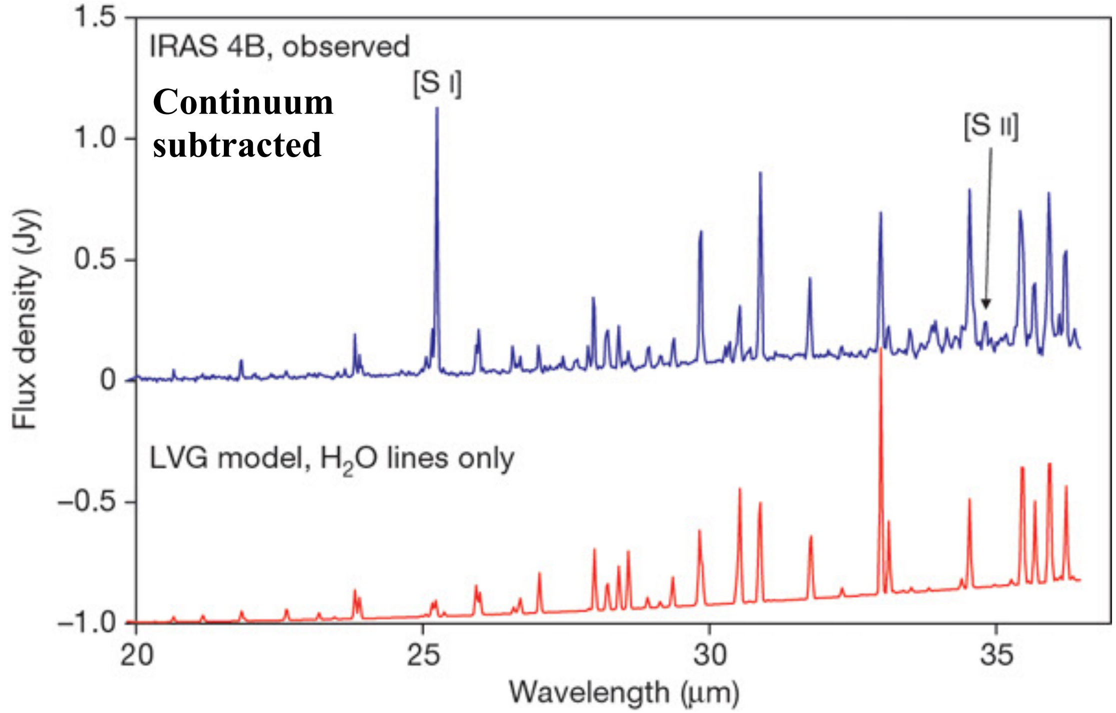
-Why do Class I sources have lower H_2O abundances and larger OH/H_2O ratio? Enhanced photodissociation? Longer timescale for freeze-out?

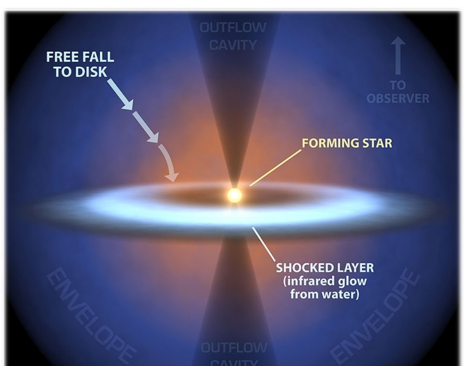
Nisini, Giannini et al. 2002

Hot water from disk accretion shock?



Deeply embedded Class 0 protostar



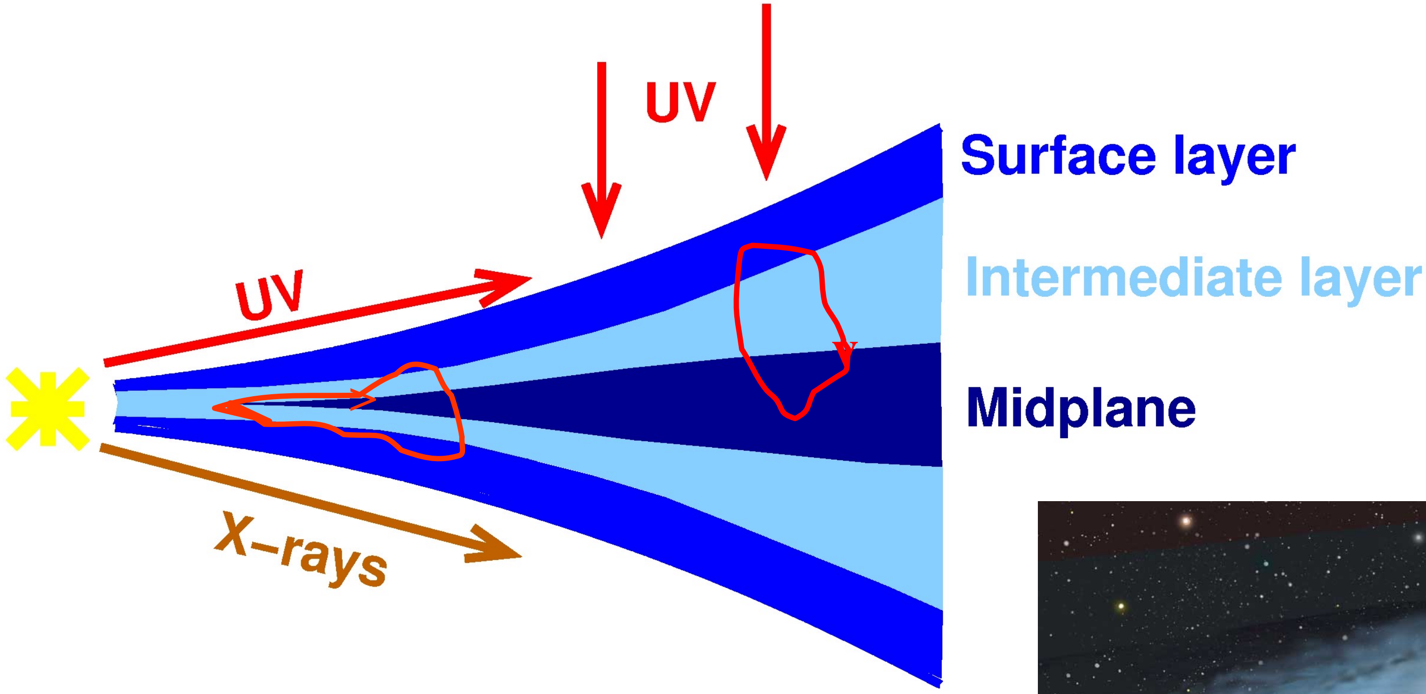


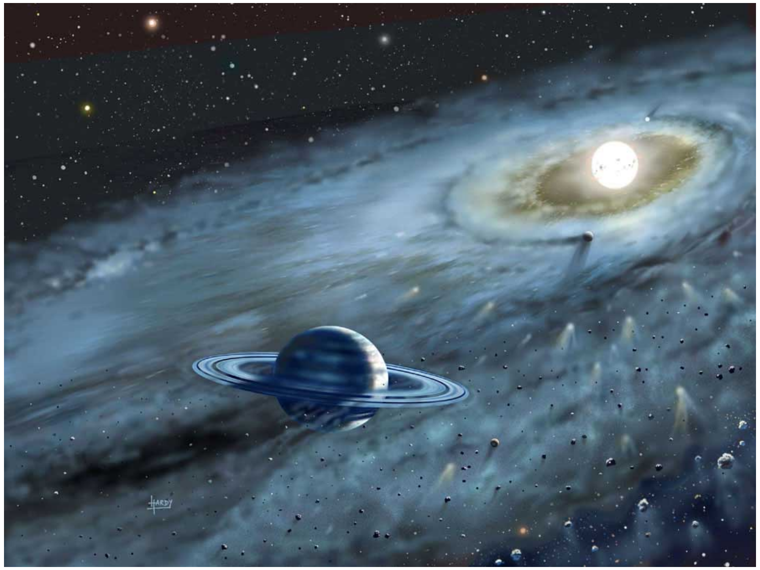
T=170 K, n>10^9 cm^{-3}

Q: Chemical signatures of accretion disks?
How is material modified as it is incorporated into disk?

Watson et al. 2007

Where is water in protoplanetary disks?

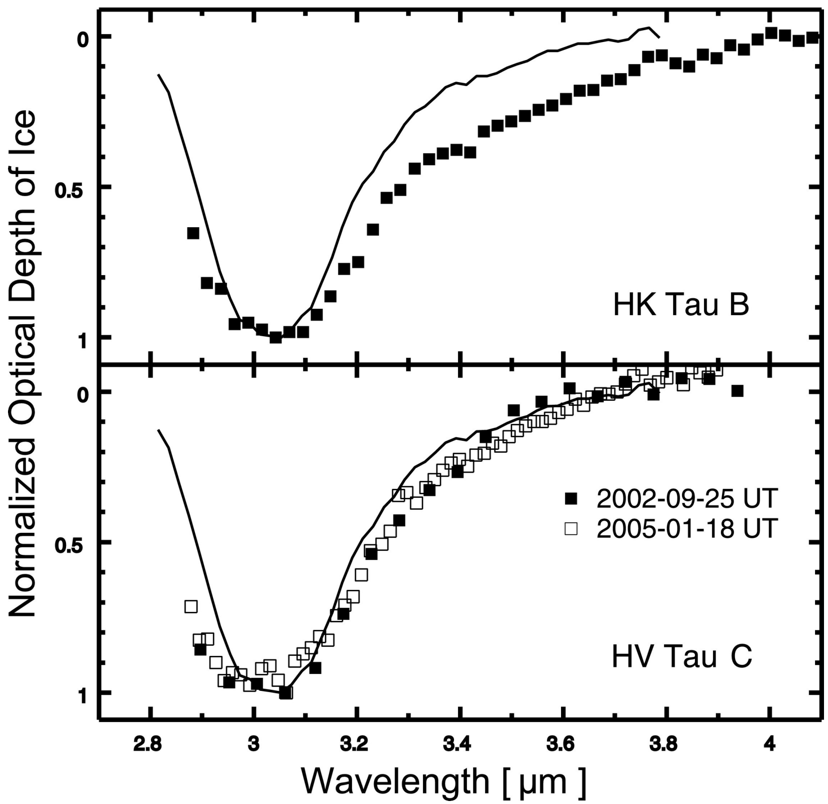


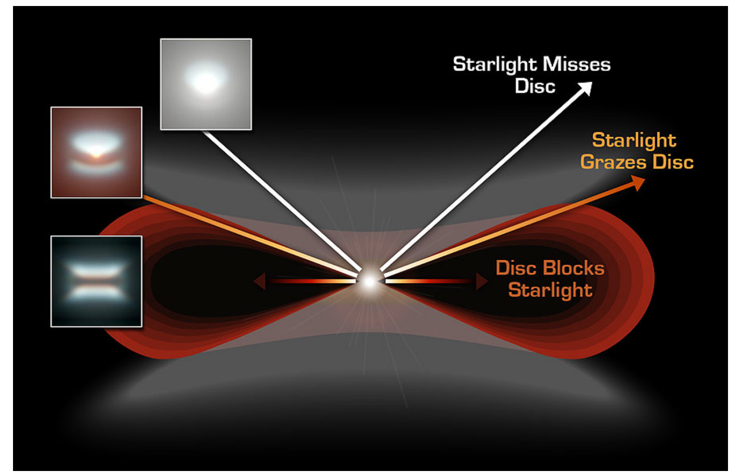


Q: use water as tracer of radial and vertical mixing? Probe snow line?

JWST + Herschel

H_2O ice in disks

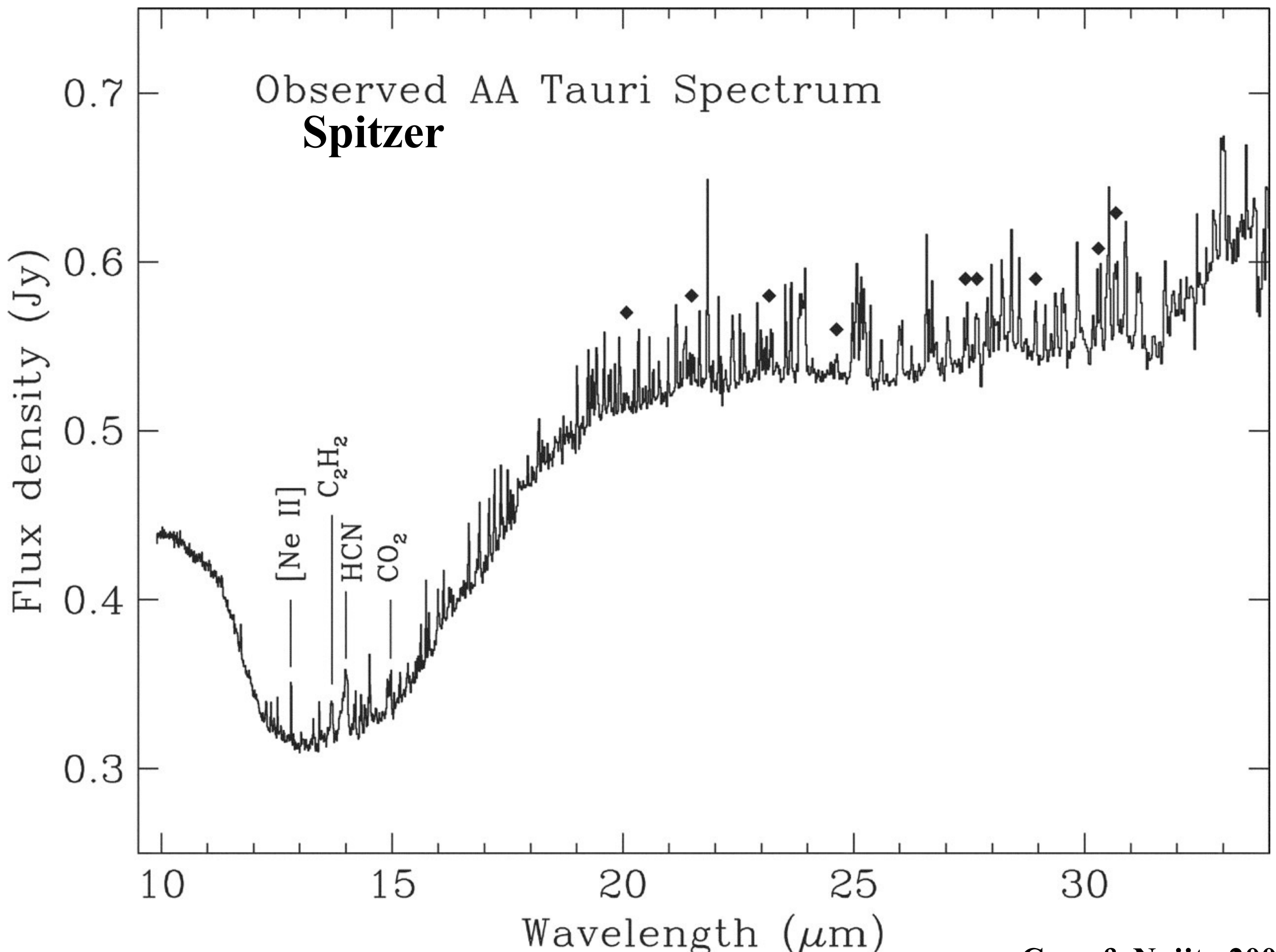




Terada et al. 2007, Pontoppidan et al. 2005

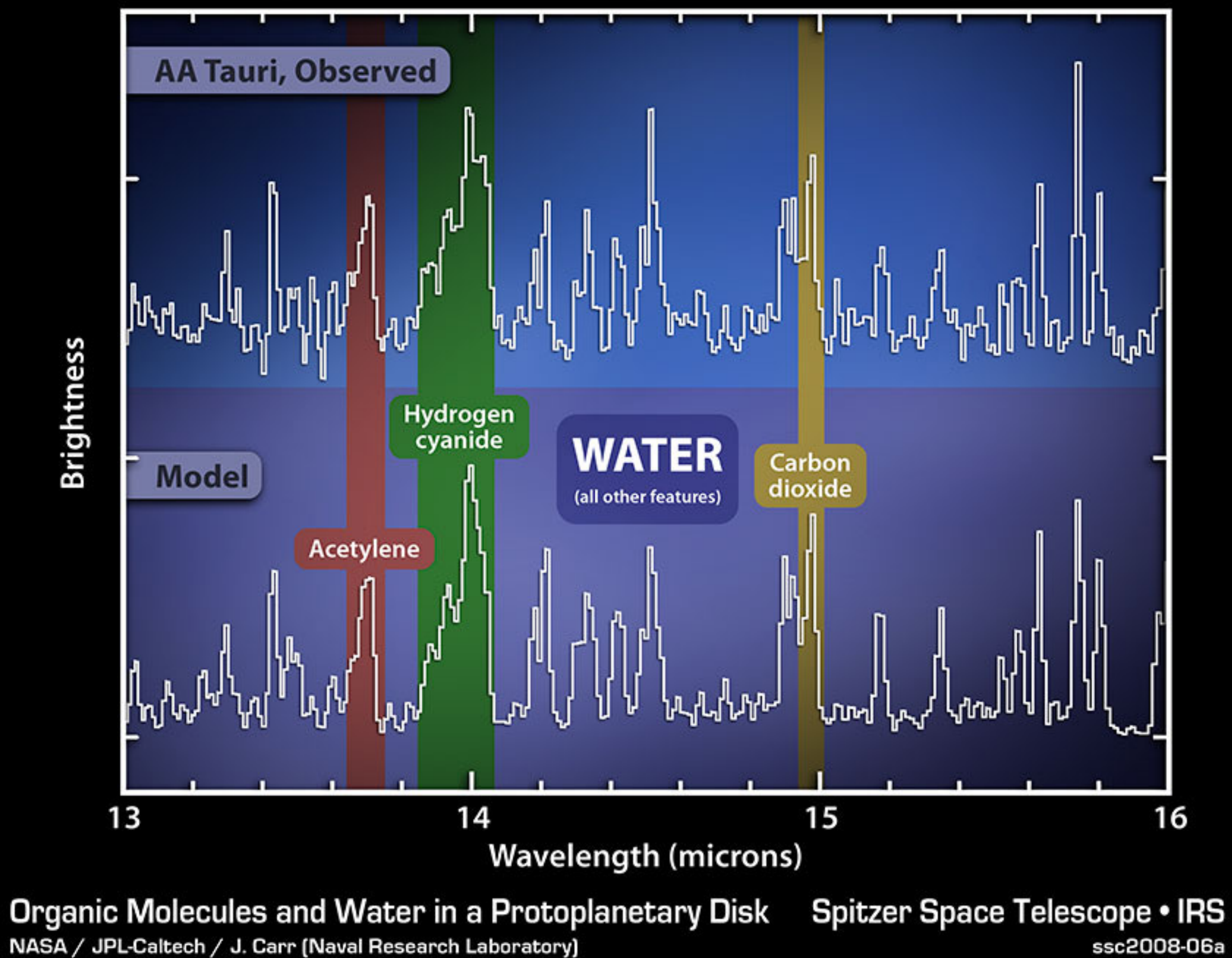
Q: how much water gas is in outer disk?

Water and organics in inner disk



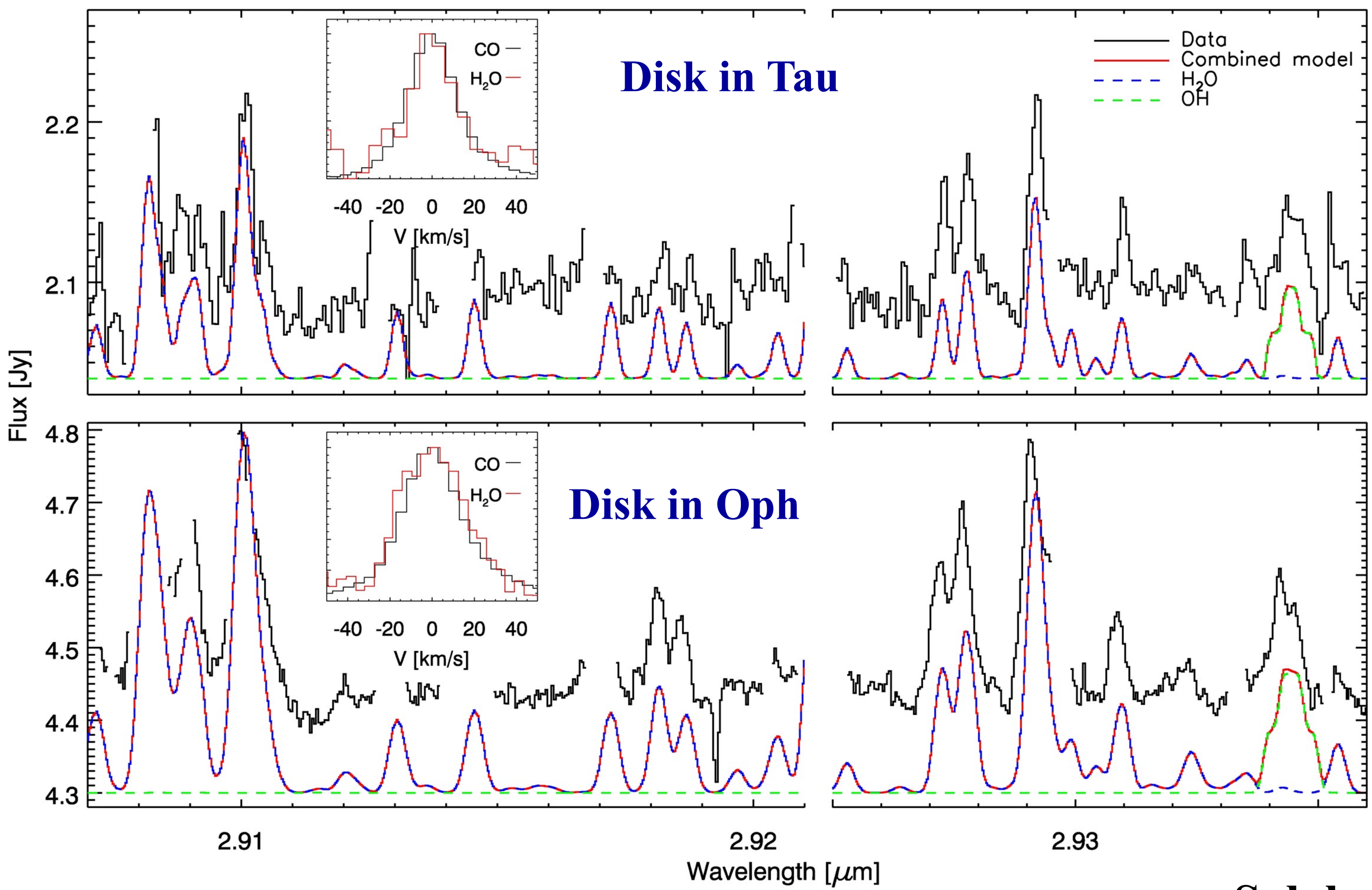
Carr & Najita 2008
Salyk, Pontoppidan etal. 2008

Hot water and organics in inner disk



Carr & Najita 2008
Salyk, Pontoppidan et al. 2008

Near-IR H_2O and OH in disks from ground



Keck R=25000

Fully resolved with CRIRES

E_u~5000-10000 K

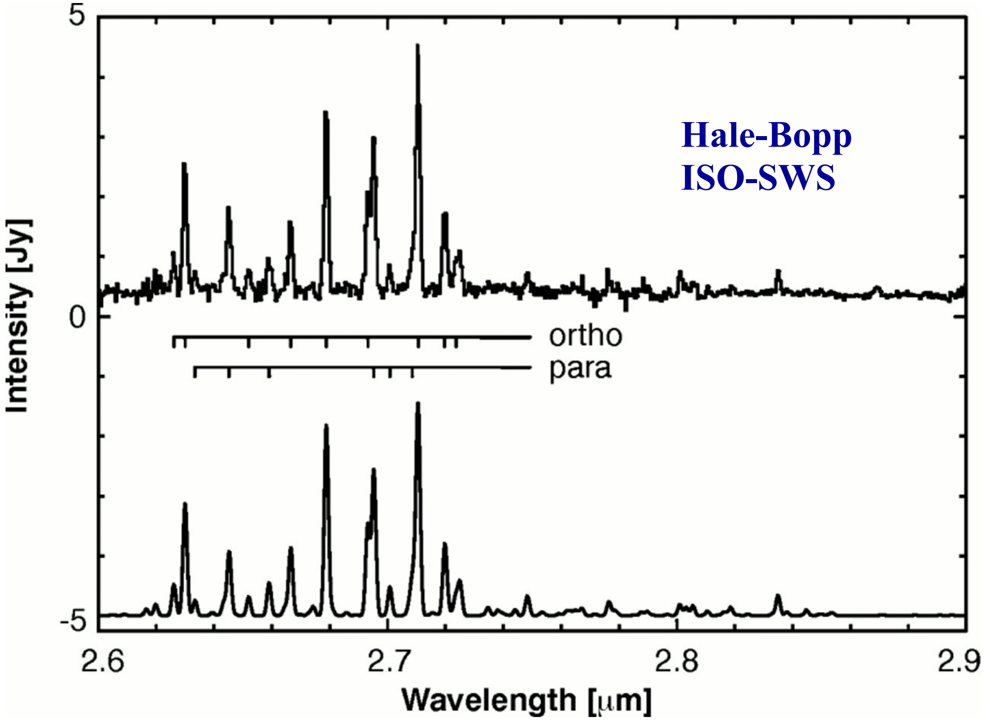
Salyk et al. 2008

H_2O/CO~10, H_2O/OH~3-4, T=1000 K
⇒ H_2O and OH come from inner 0.5-1 AU!

Implications

- Water gas is found well inside the ‘snow’ line (estimated at ~3 AU)
- Water is expected to disappear in ~10^5 yr $\Rightarrow$ replenishment needed
- Inward radial migration or upward mixing of icy grains and planetesimals, followed by evaporation?

Water in comets



Crovisier et al. 1997
Dello Russo et al. 2005

$T_{o/p}$=23 - >30 K, Linked to formation temperature in disk or cloud?

Q: - Formation temperature and history (from o/p ratio)?
- Source of water on Earth (from HDO/H_2O)?

Conclusions

- H_2O found throughout universe: ‘waterworld’
- H_2O abundance varies greatly from region to region
- Model scenarios available, but many questions remain

- Herschel HIFI and PACS will provide our best chance for decades to ‘nail down’ gaseous H_2O and OH in galaxies, evolved stars, clouds, YSOs, outer disks
- Need SOFIA for spectrally resolved [O I]
- Need JWST, SOFIA, ELTs for hot gas in inner disk
- Need JWST, ground for ice mapping
- Need complementary laboratory data, theoretical studies of collision rates, and good radiative transfer codes!