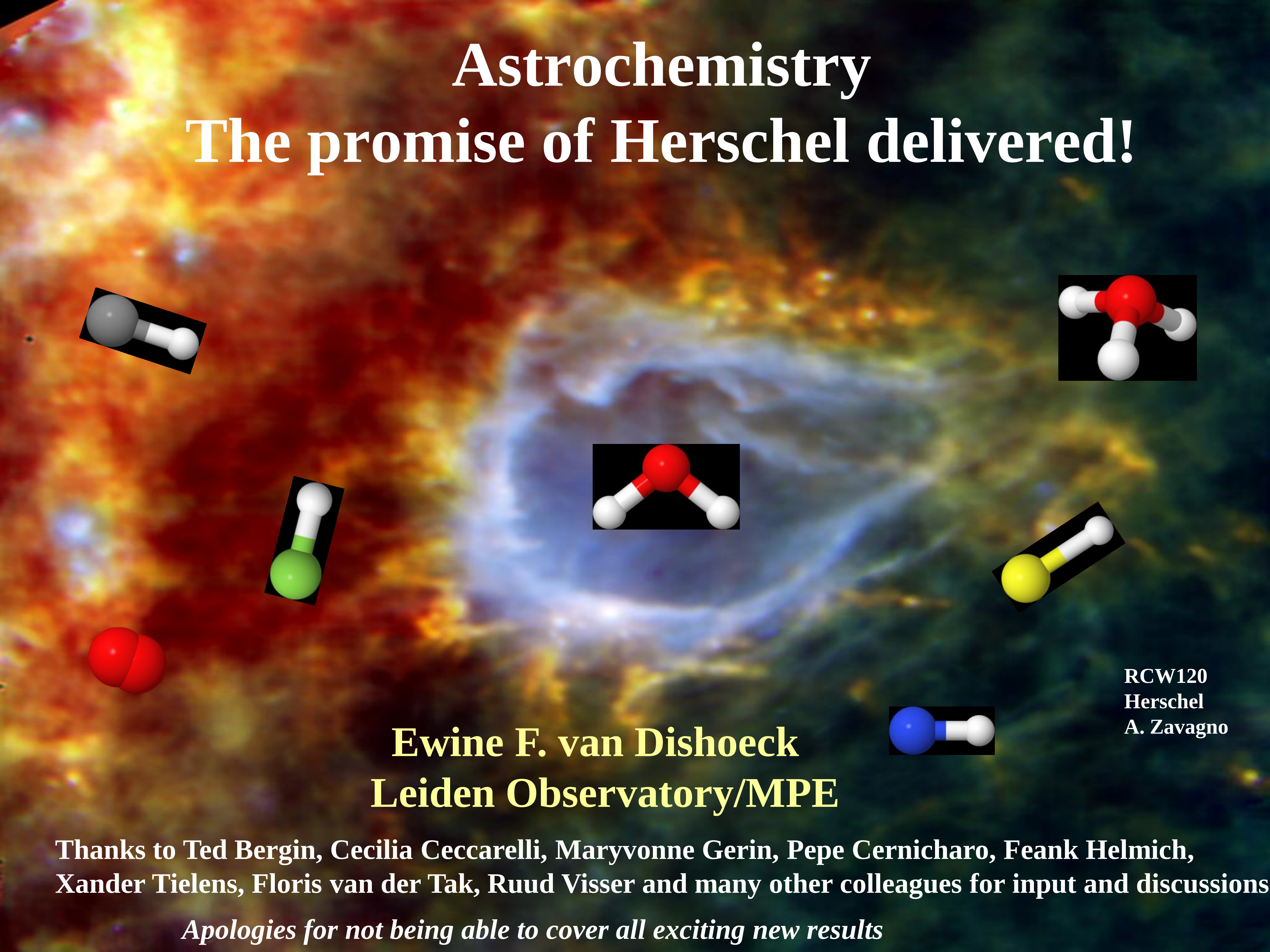


Astrochemistry
The promise of Herschel delivered!

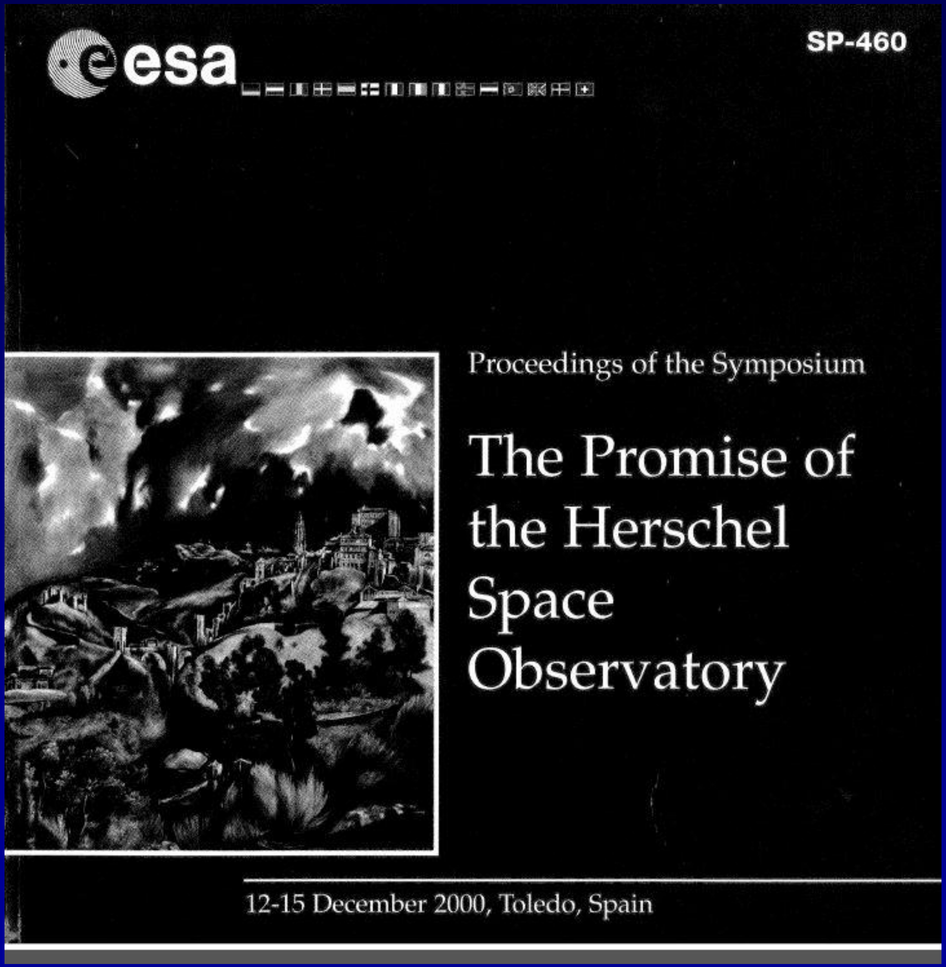
RCW120
Herschel
A. Zavagno

Ewine F. van Dishoeck
Leiden Observatory/MPE

Thanks to Ted Bergin, Cecilia Ceccarelli, Maryvonne Gerin, Pepe Cernicharo, Feank Helmich, Xander Tielens, Floris van der Tak, Ruud Visser and many other colleagues for input and discussions

Apologies for not being able to cover all exciting new results

Many decades of planning....



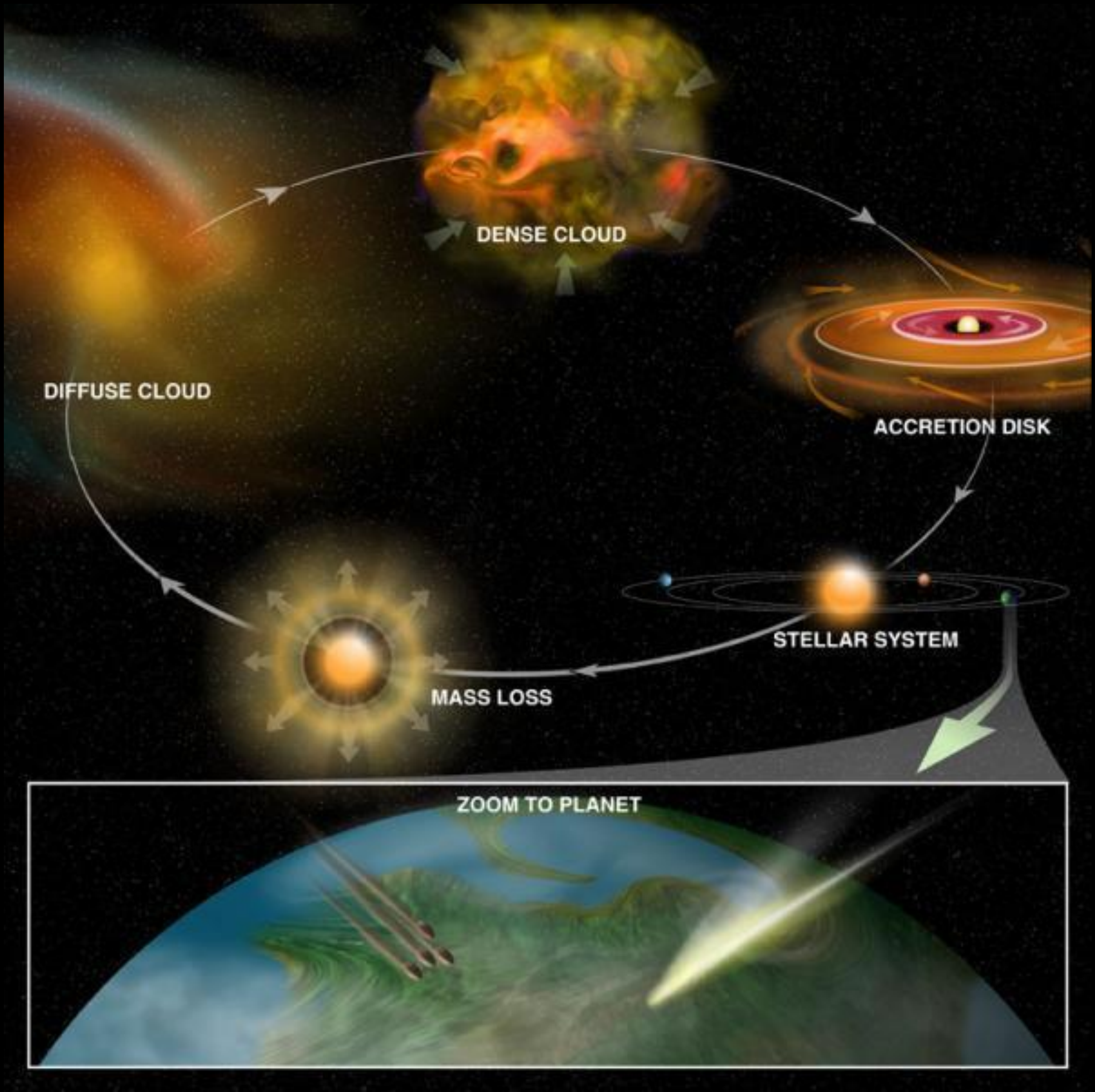
Science cases dating back to late 1970's highlighting astrochemistry as a major driver

Thanks to many astrochemists for making the case for Herschel!

Herschel astrochemistry drivers

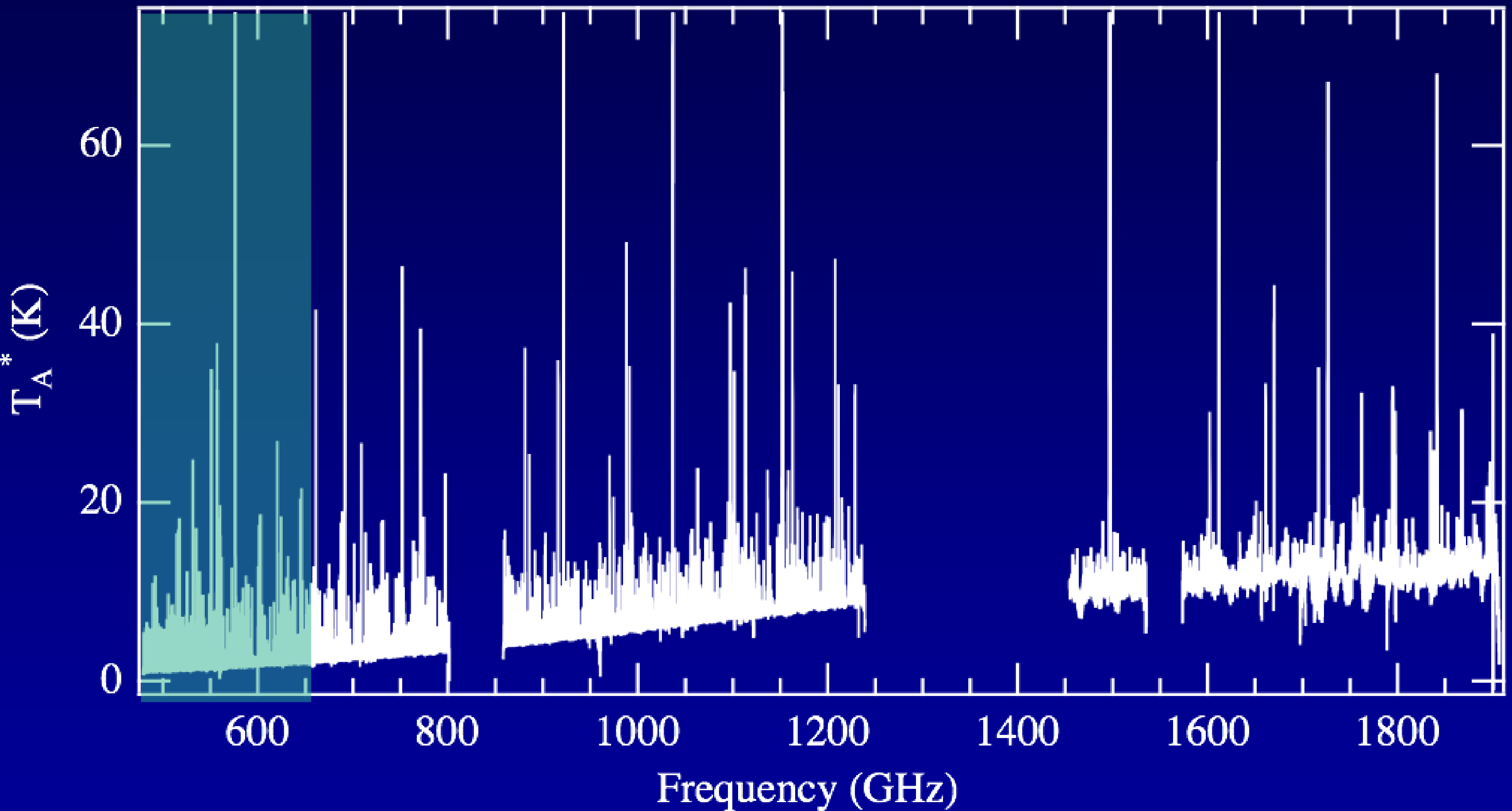
- Hydrides
- Water
- O_2
- Unbiased spectral surveys

Cosmic cycle of gas and dust



B. Saxton
NRAO/AUI

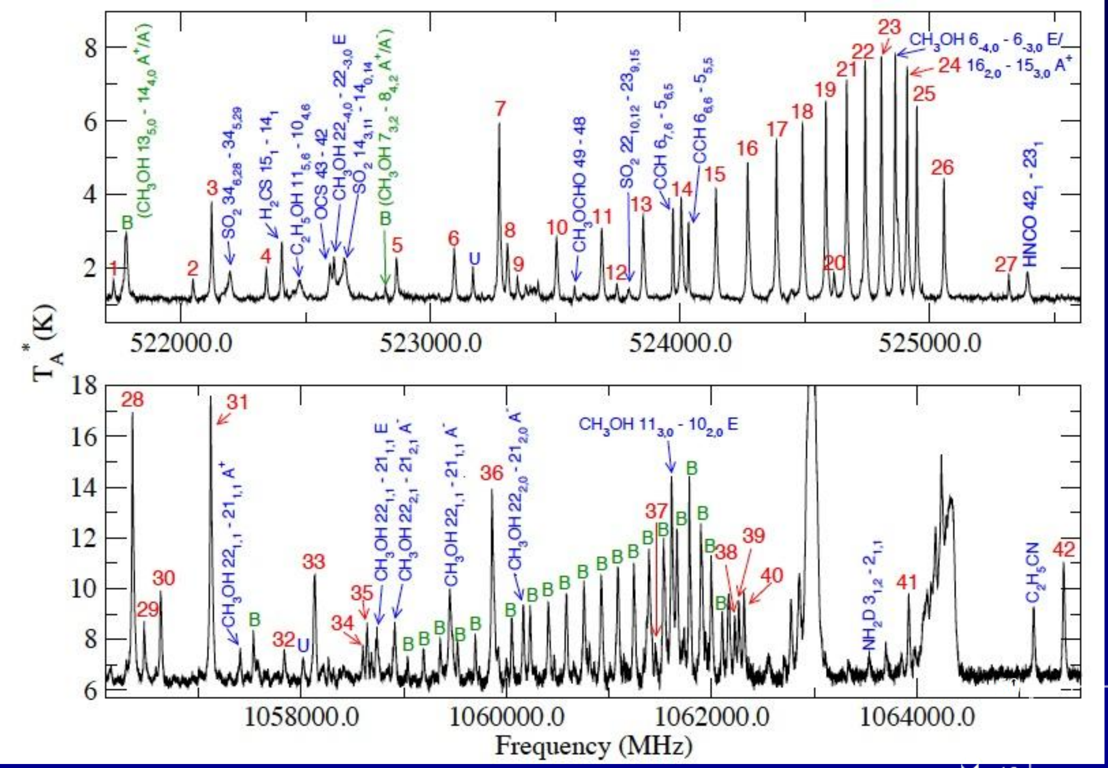
The power of Herschel spectroscopy delivered



Bergin, Crockett et al. 2010

Entire spectrum in just tens of hours!

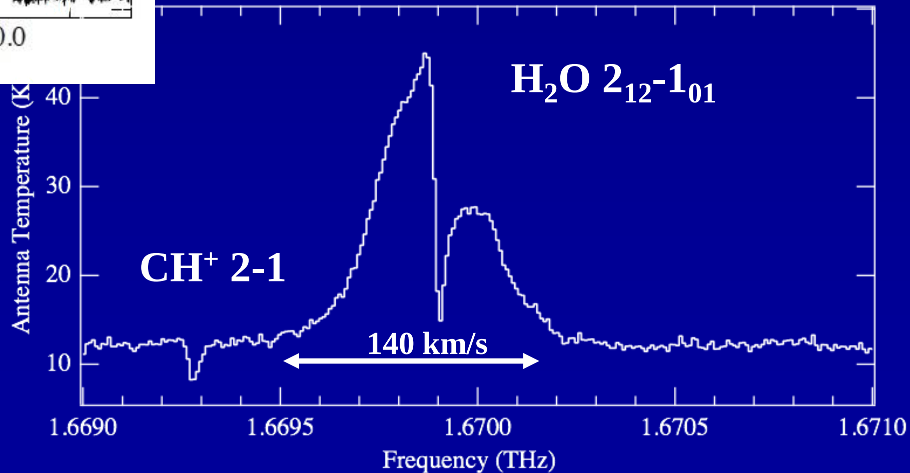
The power of Herschel spectroscopy



Orion-KL
HEXOS

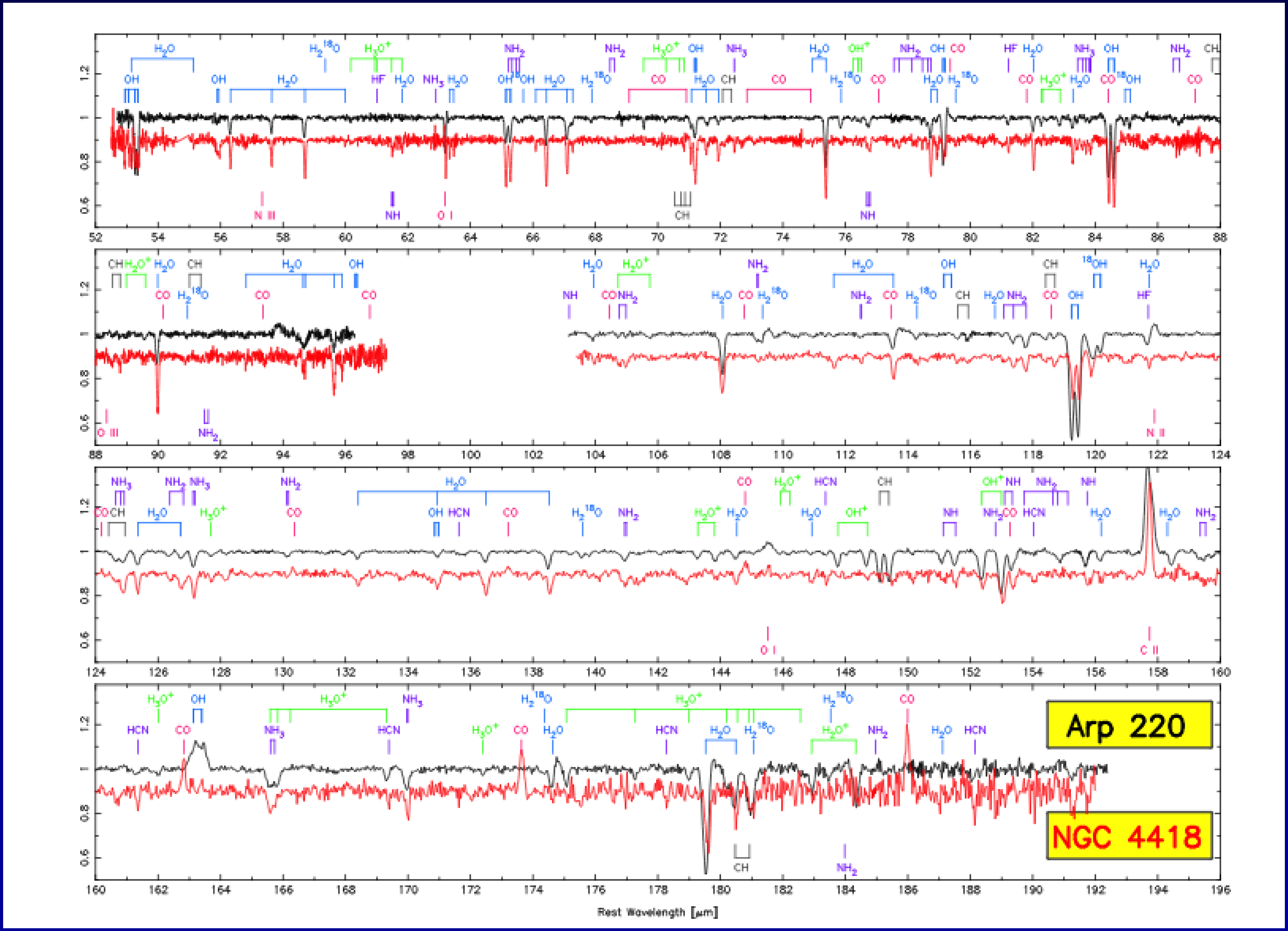
Wang, Bergin et al. 2011

High-quality line profiles, even at 1.67 THz!



Crockett et al. 2010

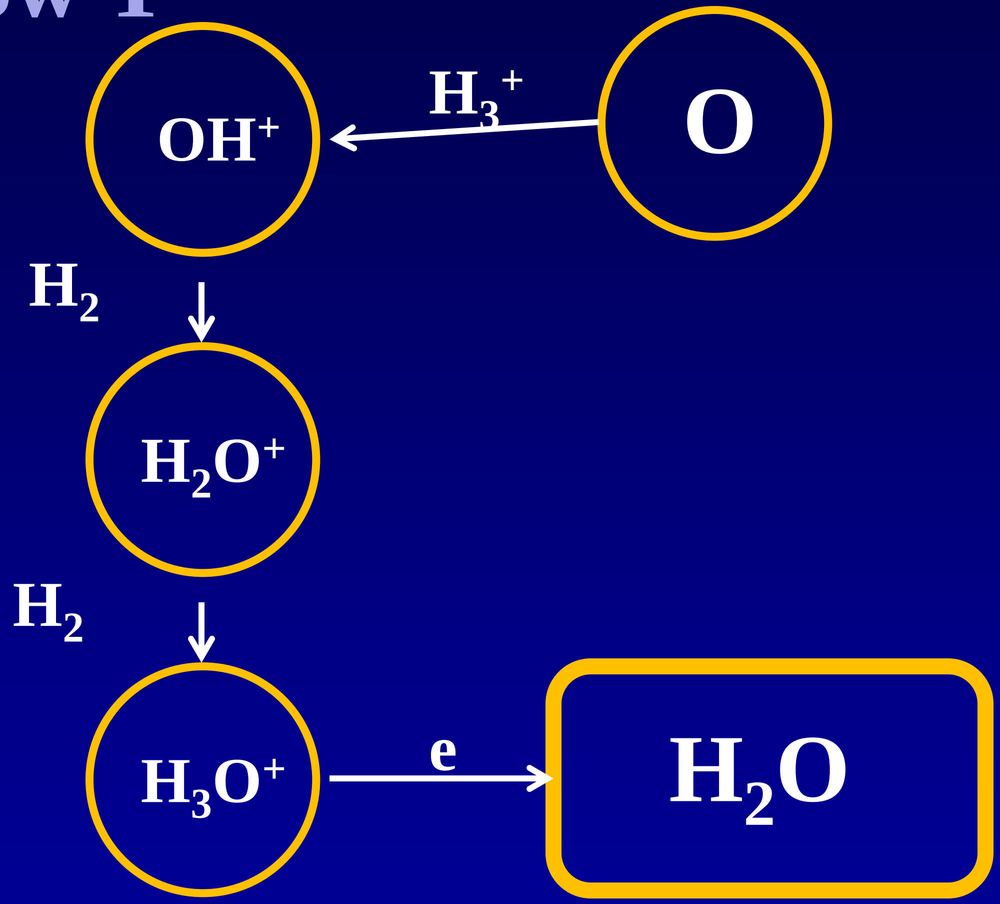
From galactic to extragalactic astrochemistry!

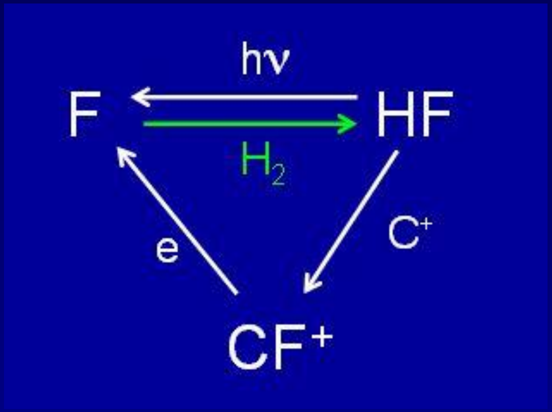


Gonzalez-Alfonso et al. 2012, Herschel-PACS

Testing hydride chemistry

Low T

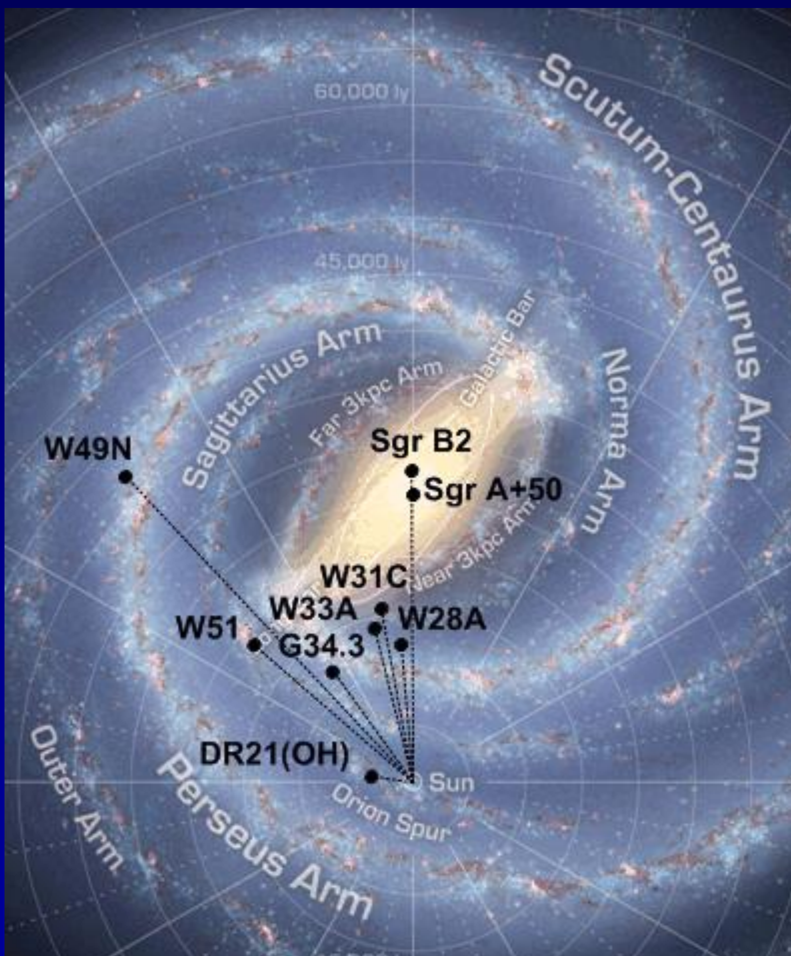




Light molecules
→ High frequencies

Ion-molecule reaction schemes developed in early 1970's but many of the intermediate building blocks cannot be observed from ground

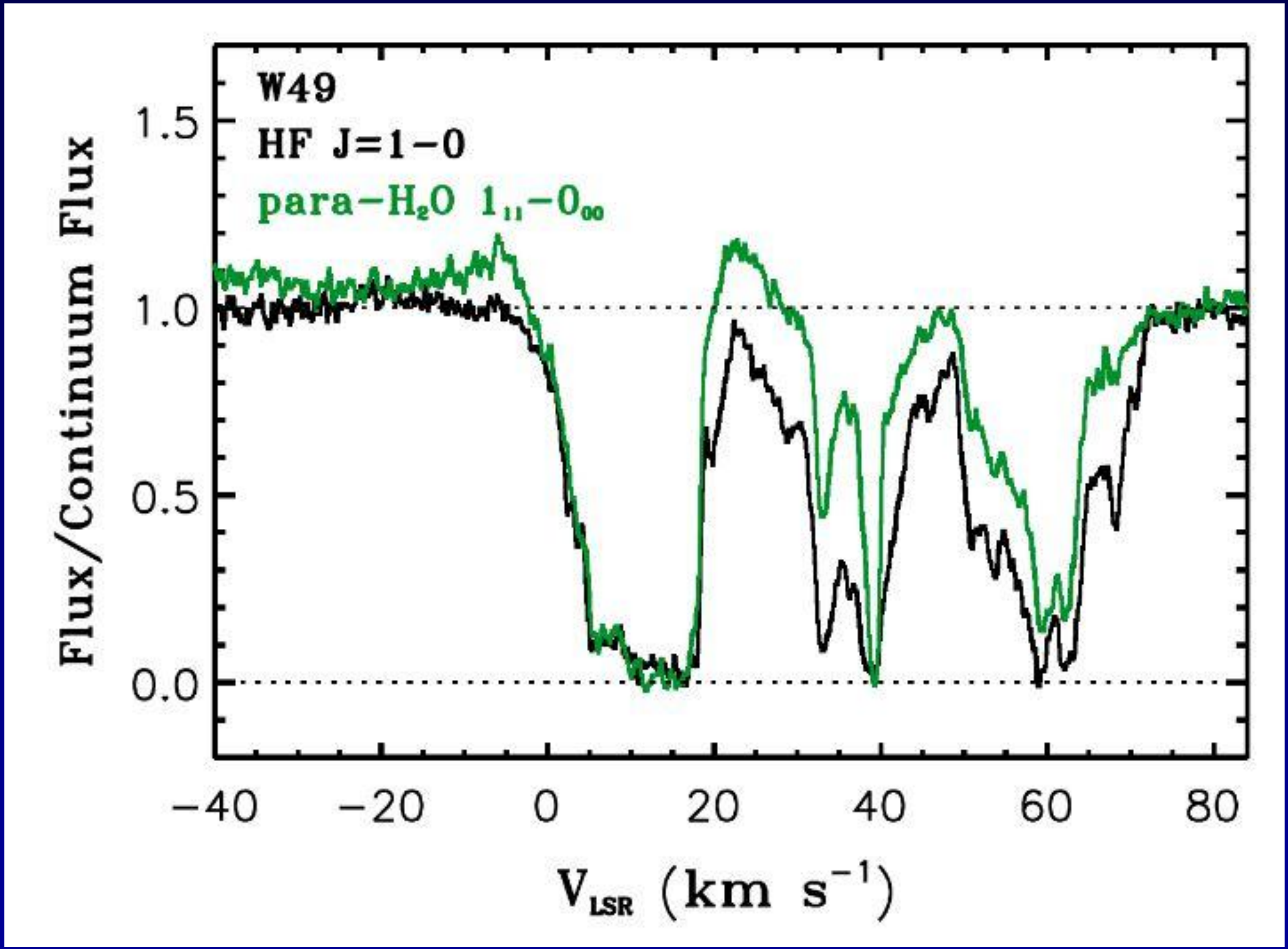
Testing ion-molecule chemistry



- **Absorption against bright far-IR continuum**
- **Clouds A_V ~few mag**
- **All molecules in ground level→simple analysis**
- ***Precision astrochemistry* (factor of ~2)**

Gerin et al. 2010

Absorption lines

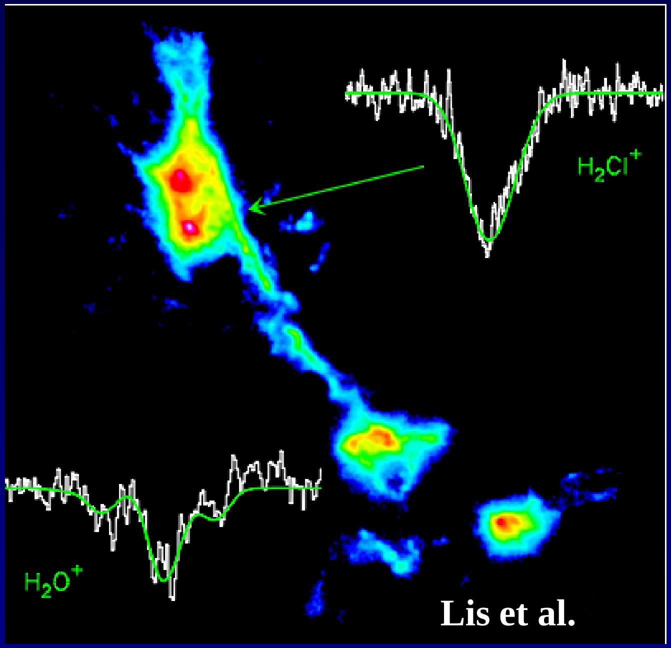


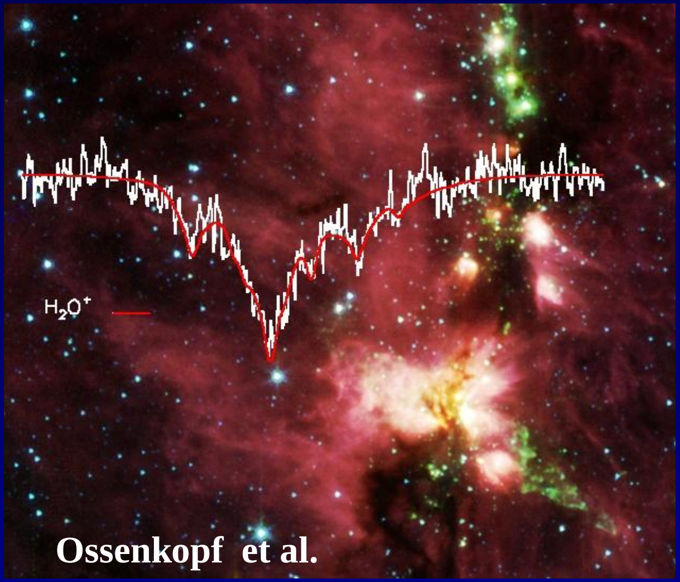
Water
o/p=3

Neufeld et al. 2010,
Sonnetrucker et al. 2010
Godard et al. 2012
Emprechtinger et al. 2012
Flagey et al. 2013

- **Diffuse and translucent clouds along the line of sight**
- **HF as tracer of H_2 column density because of simple chemistry (see C^+, GOT-C+)**
- **Constant H_2O/H_2 abundance of $5x10^{-8}$ (except GC), consistent with models**

Detection of H_2O^+, HCl^+ and H_2Cl^+

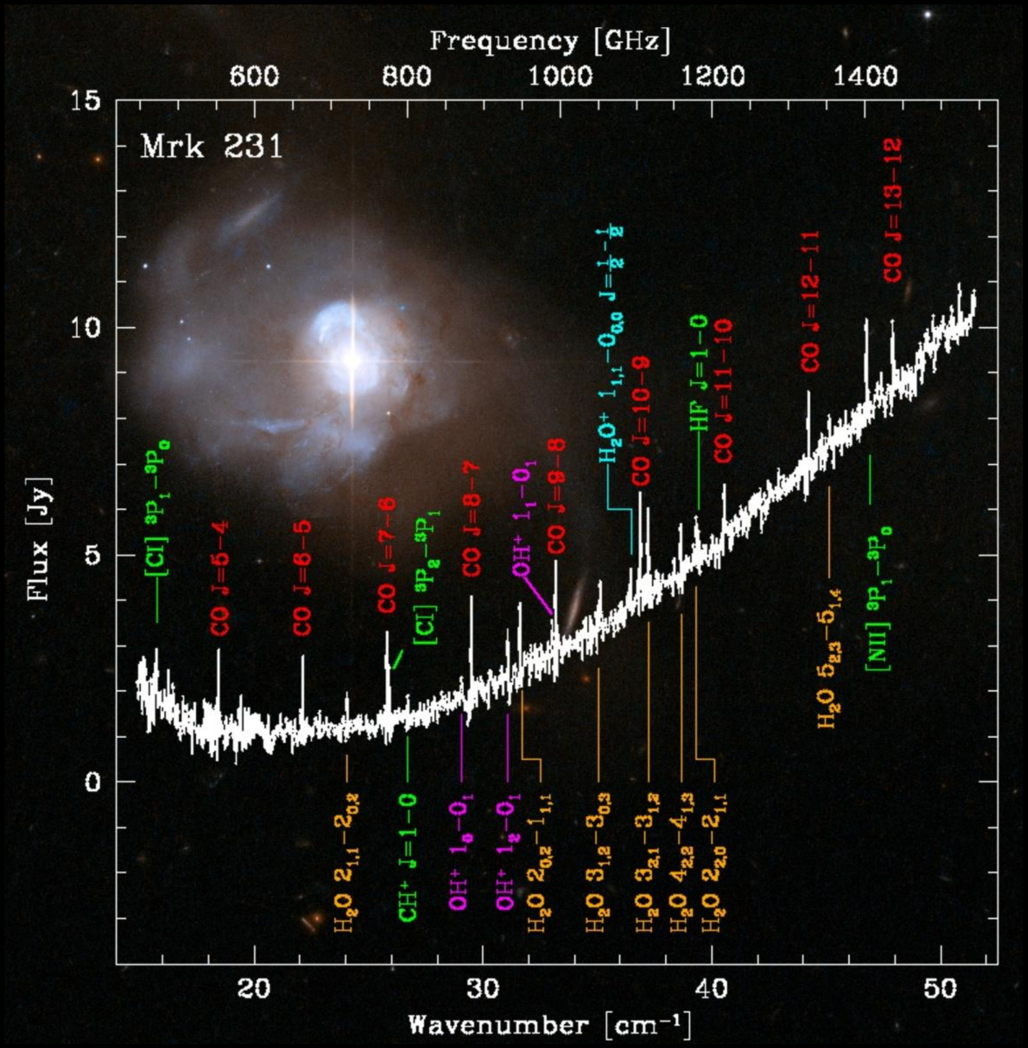




- H_2O^+ must arise in H_2 poor phase (H/H_2~10)
- HCl^+ and H_2Cl^+ detection; chemistry?
- OH^+, H_2O^+ constrain ζ

Ossenkopf et al., Benz et al., Bruderer et al., Gerin et al., Wyrowski et al., Gupta et al., Schilke et al., Lis et al. 2010; Neufeld et al. 2012, de Luca et al. 2012, Indriolo et al. 2013, Monje et al. 2013....

OH$^+$ and H$_2$O$^+$ in other galaxies!



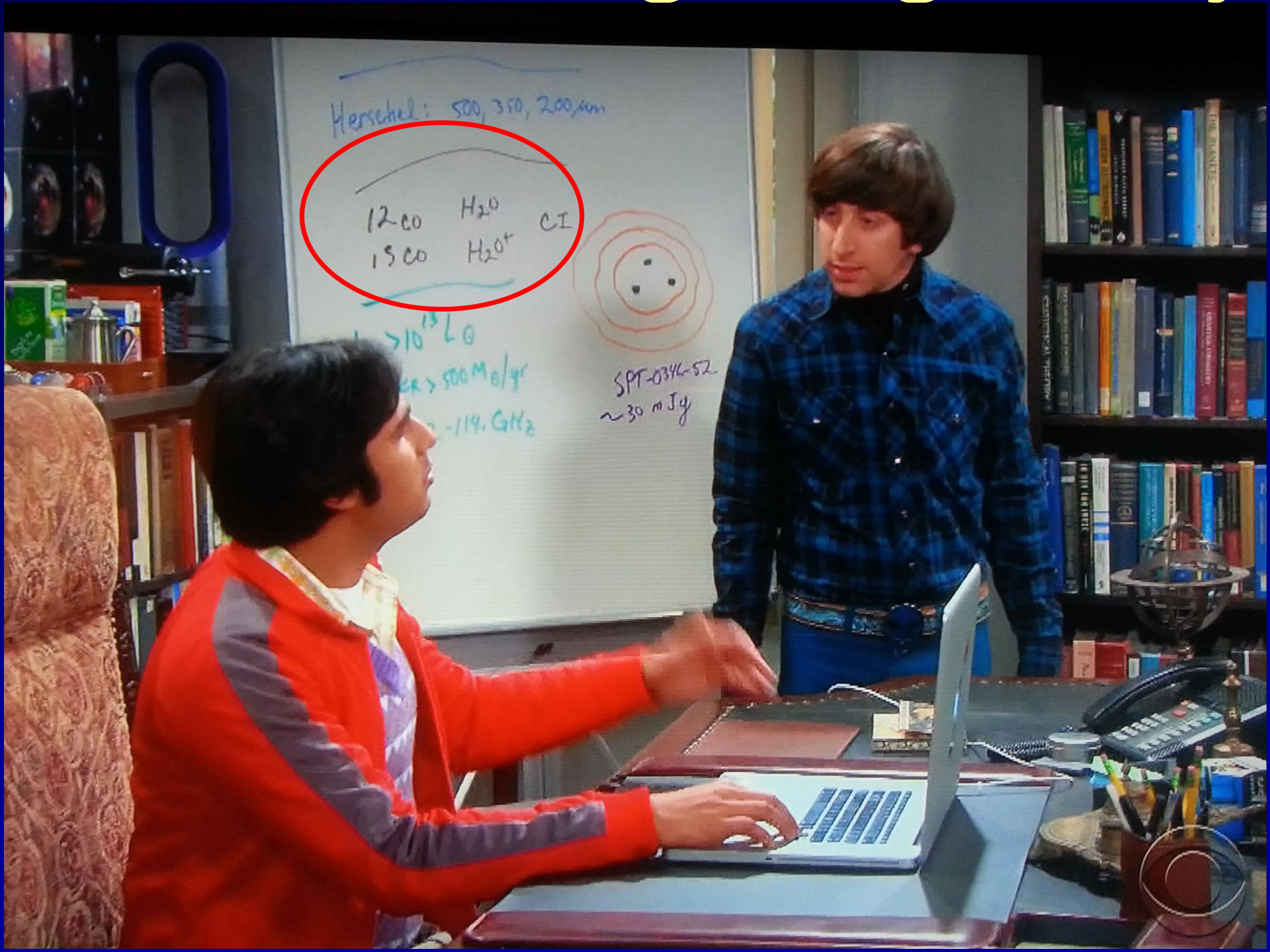
SPIRE-FTS

Van der Werf et al. 2010
Gonzalez-Alfonso et al. 2013

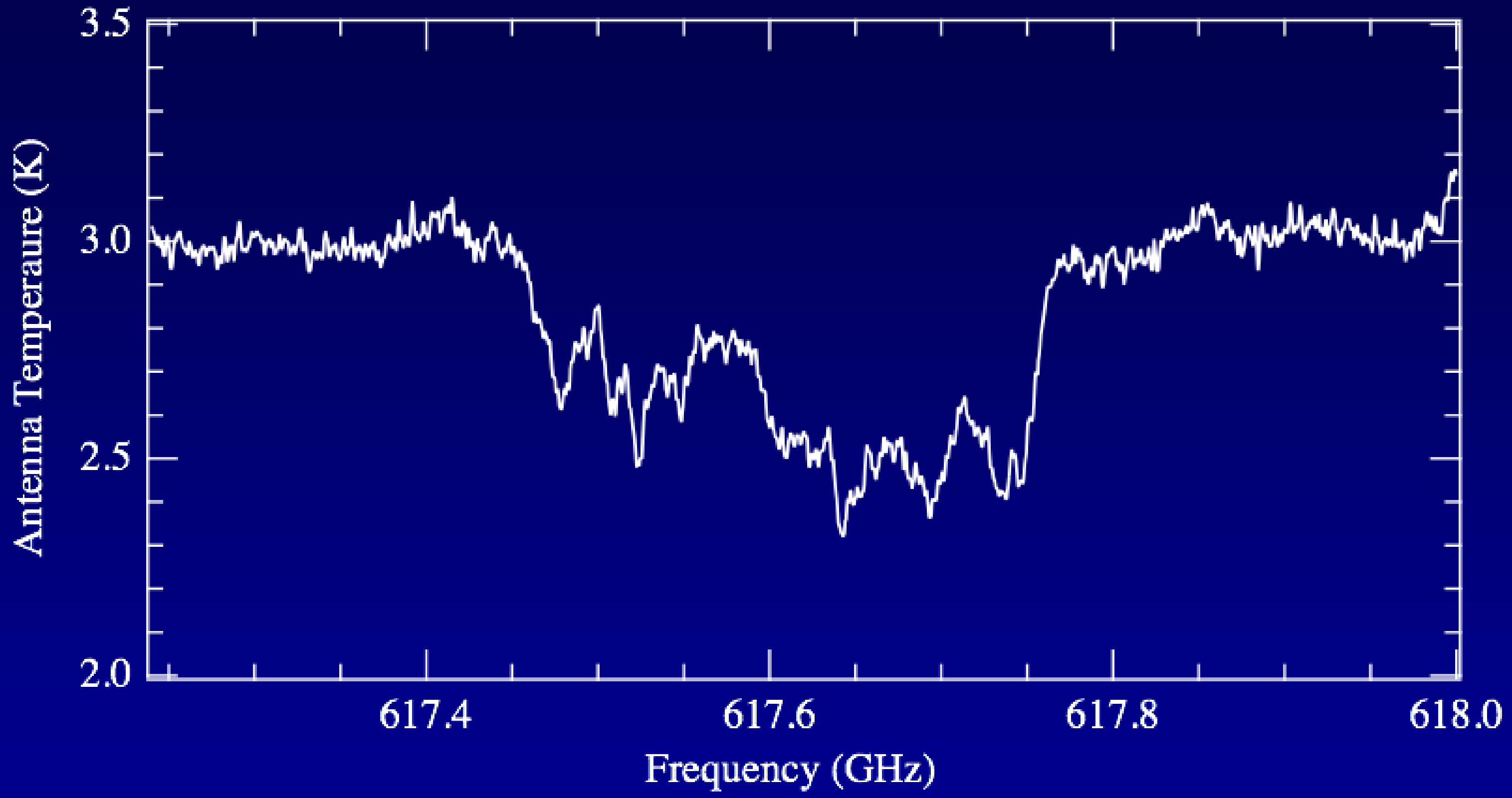
Indriolo et al. 2013

Inferred cosmic ray ionization rates $\zeta \sim 10^{-13}$ s^{-1}, >> galactic ζ

Even in the Big Bang theory



U-line SgrB2

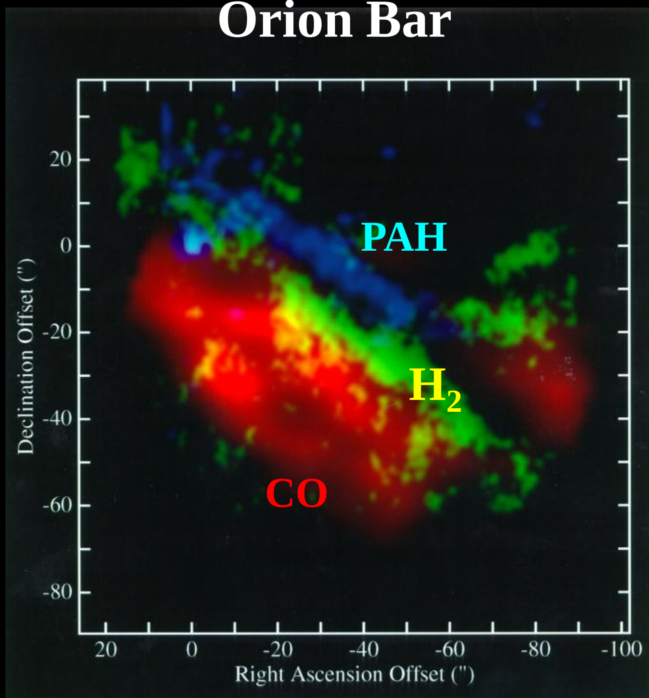


Molecule present in *all* spiral arm clouds between us and the galactic center

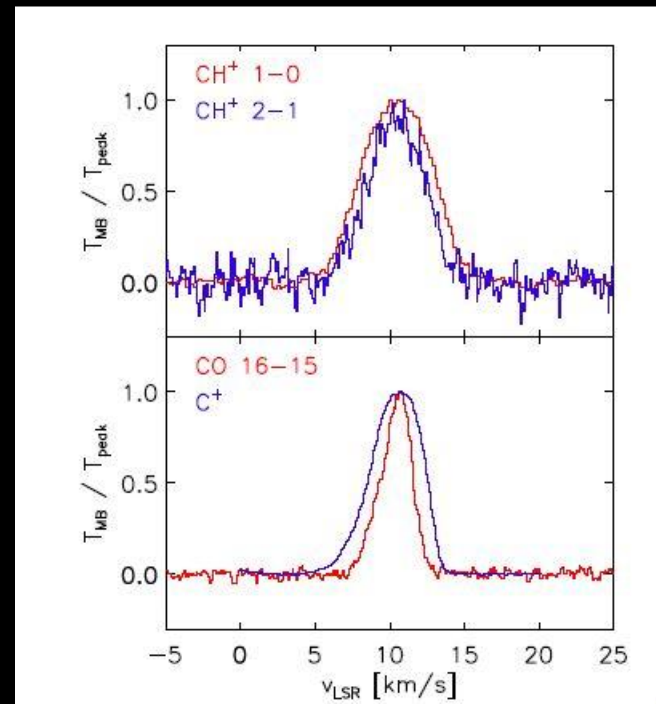
Post talk comment: feature now identified as $^{36}ArH^+$ 1-0 absorption, see Mike Barlow talk

P. Schilke

Dense PDRs: Excitation and formation processes



Tielens et al. 1993, Hogerheijde et al. 1995



HF: van der Tak et al. 2012, CH^+: Nagy et al. 2013, J. Black

HEXOS, WADI

- Excitation by electrons significant in PDRs
- Formation pumping, e.g. $C^+ + H_2 \rightarrow CH^+(v,J) + H$
- State specific processes, e.g. $C^+ + H_2(v,J) \rightarrow CH^+ + H$

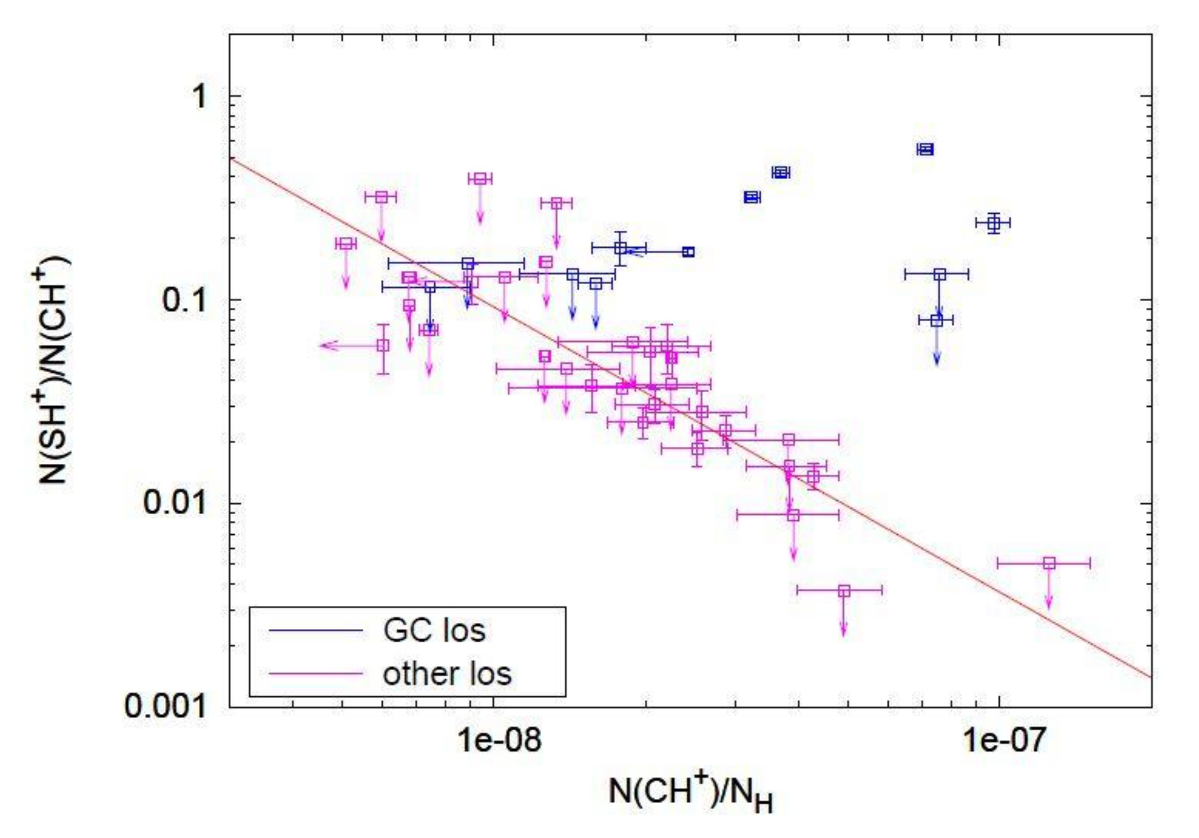
See case of CH^+, SH^+ turbulent chemistry, H_3O^+ excitation later in conference

Turbulence driven chemistry

$C^+ + H_2 \rightarrow$
$CH^+ + H +$ 4640 K

$S^+ + H_2 \rightarrow$
$SH^+ + H +$ 9860 K

Godard et al. 2012

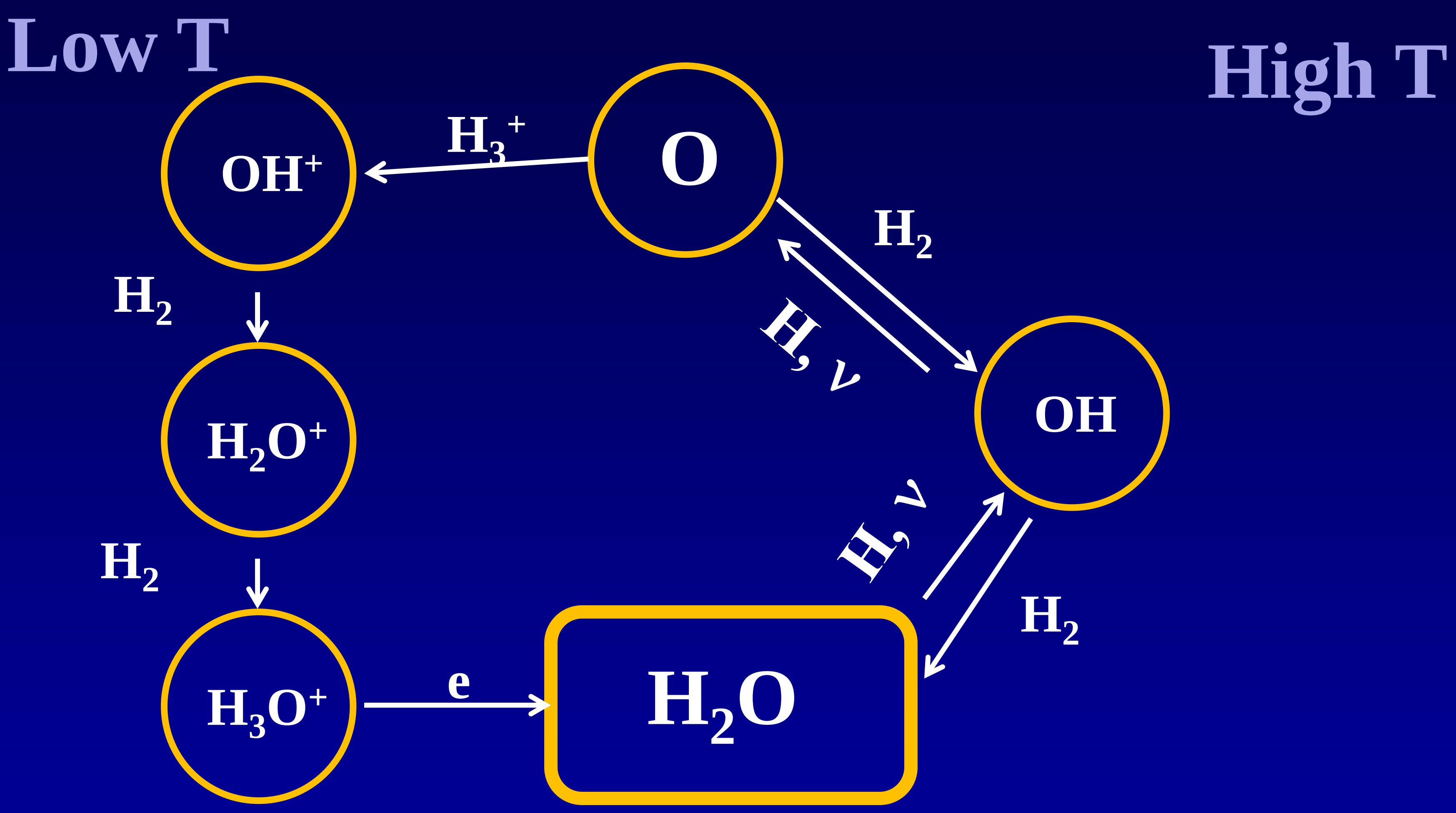


Menten et al. 2011
SH^+

Falgarone et al. 2010
CH^+

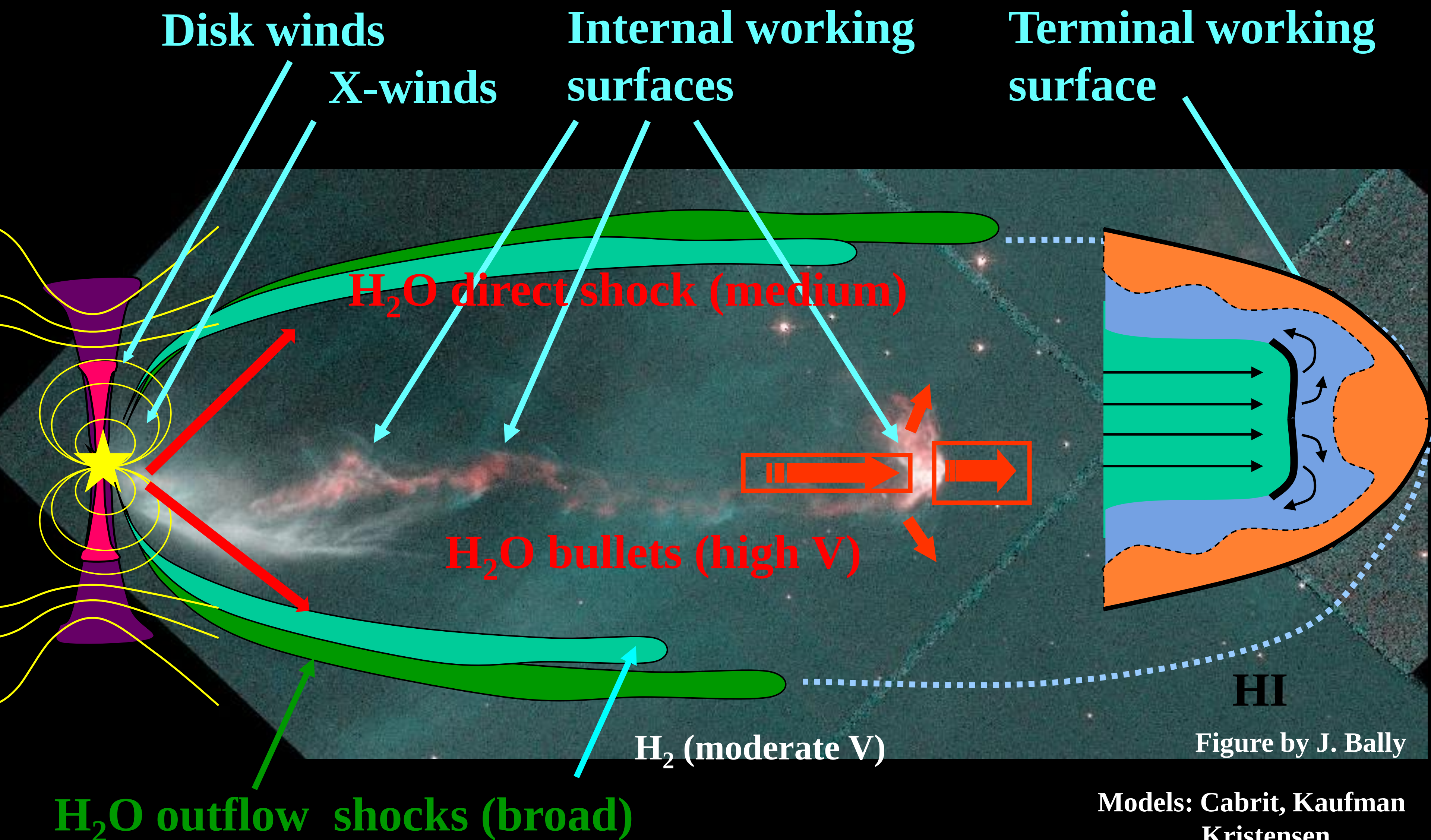
- Large column densities CH^+ mystery since its discovery in 1937
- Line widths SH^+, CH^+ larger than those of CH, CN: ~4 vs 2 km s^{-1}
- Endothermic reactions driven by turbulent dissipation?

High temperature chemistry: shocks



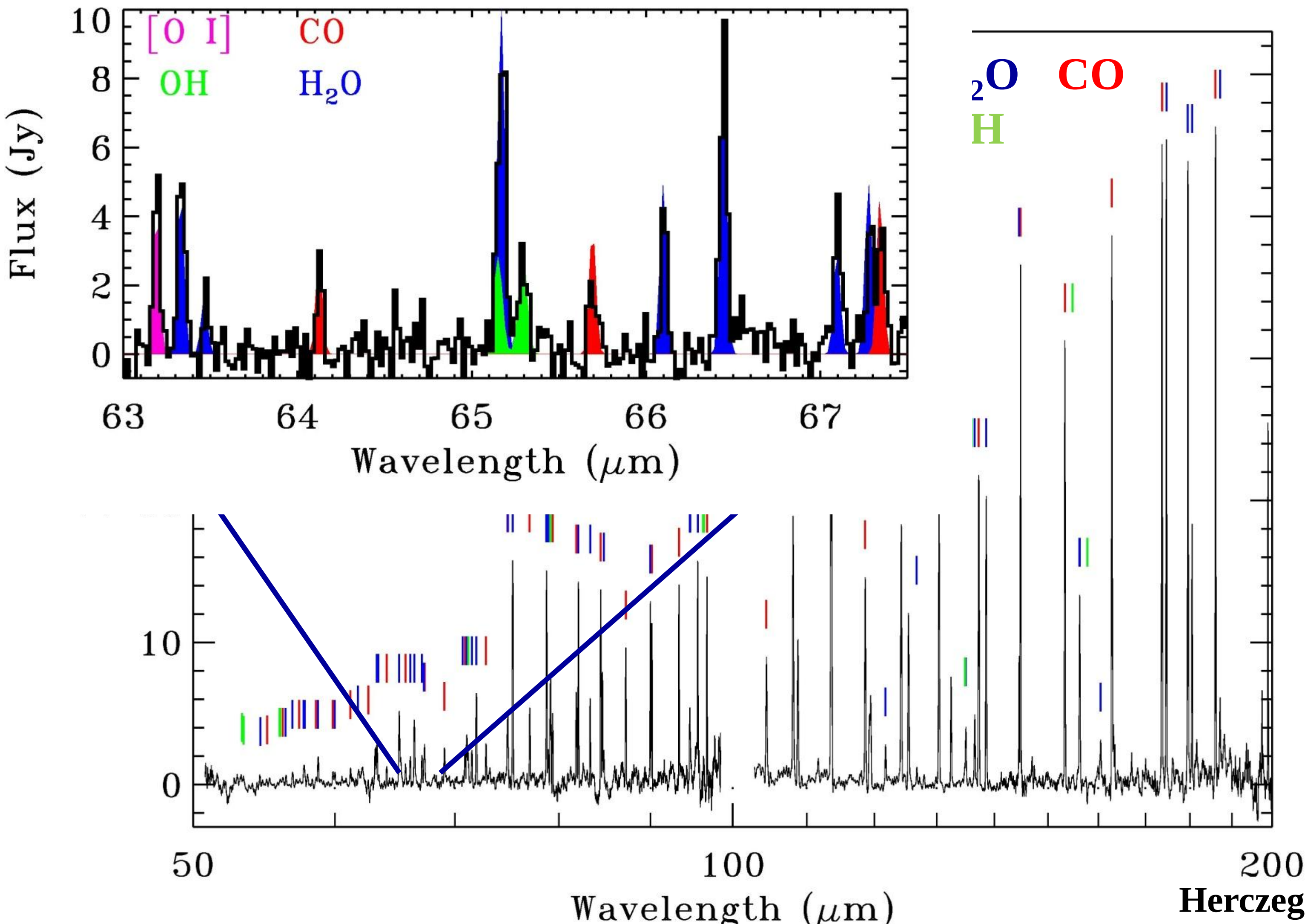
- Need high temperatures (> ~300 K) to overcome reaction barriers
- Expect all oxygen to be driven into water: H_2O/H_2 ~$6x10^{-4}$

Physics and chemistry of outflows:
Jets, winds ⇒ wide-angle UV irridiated cavities



Models: Cabrit, Kaufman Kristensen

PACS spectroscopy of shocks: Hot H_2O, OH and CO



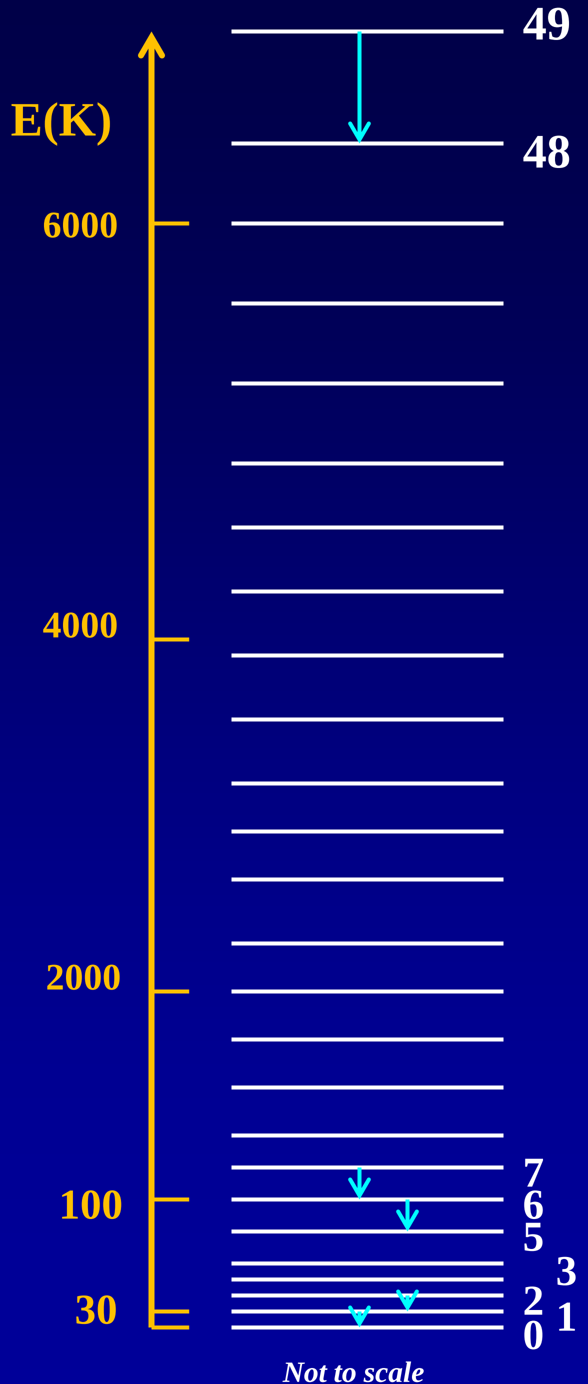
Low-mass protostar

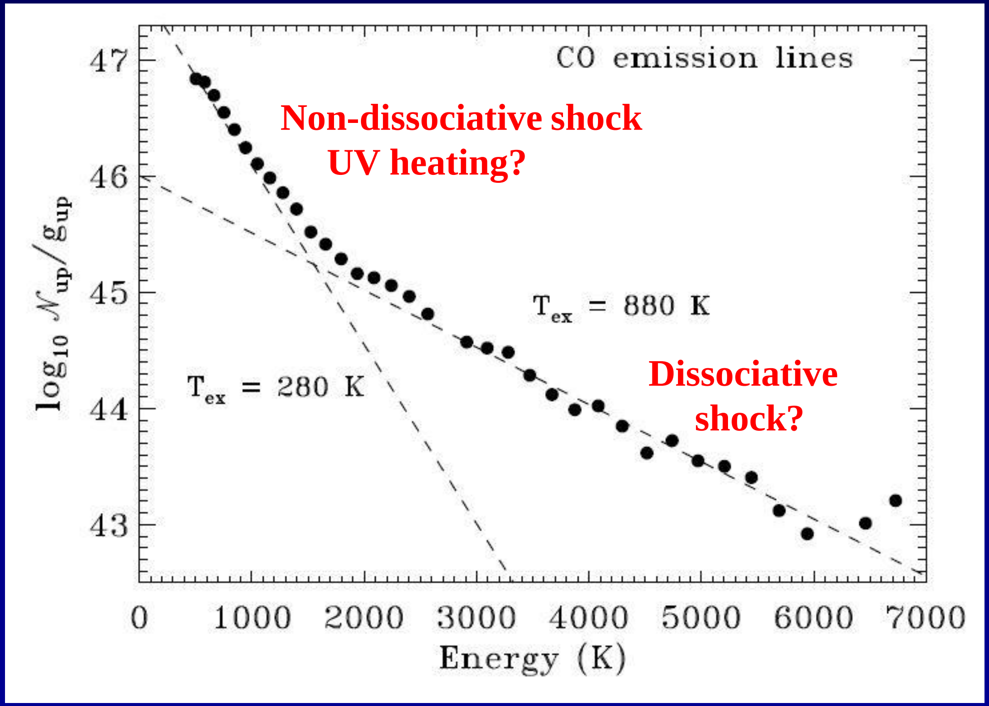
NGC1333 IRAS4B (cont. subtr.)

- Quantify excitation, abundances and main coolants of warm gas

Herczeg et al. 2012
Goicoechea et al. 2012, 2013

The CO ladder as a physical probe

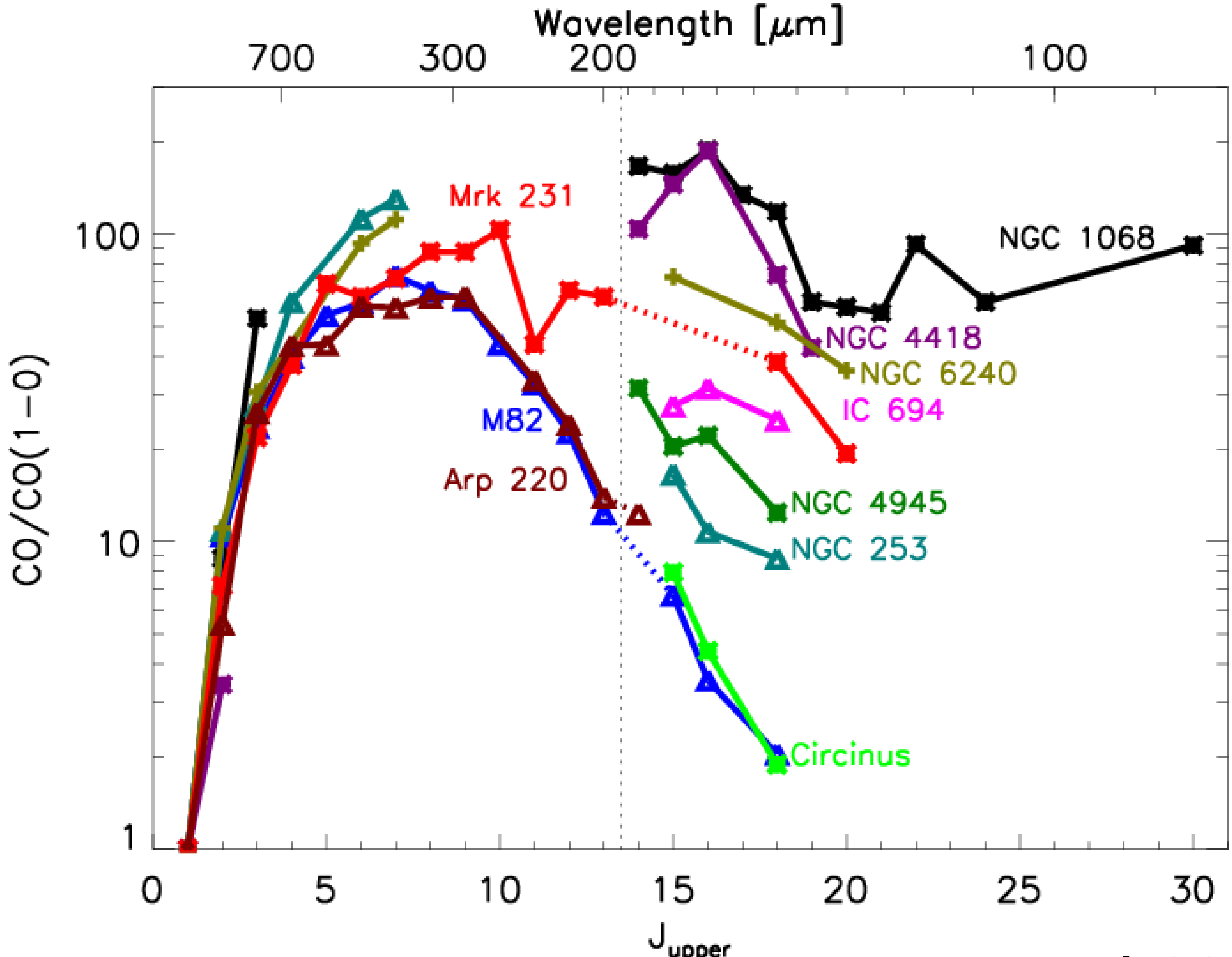




WISH, DIGIT,
HOPS

Herczeg et al. 2012
Van Kempen et al. 2010, Benedettini et al. 2012
Goicoechea et a;. 2012, Karska et al. 2013
Manoj et al. 2013, Green et al. 2013
Dionatos et al. 2013, Kristensen et al. 2013,
Visser et al. 2012

Extragalactic CO SLEDs

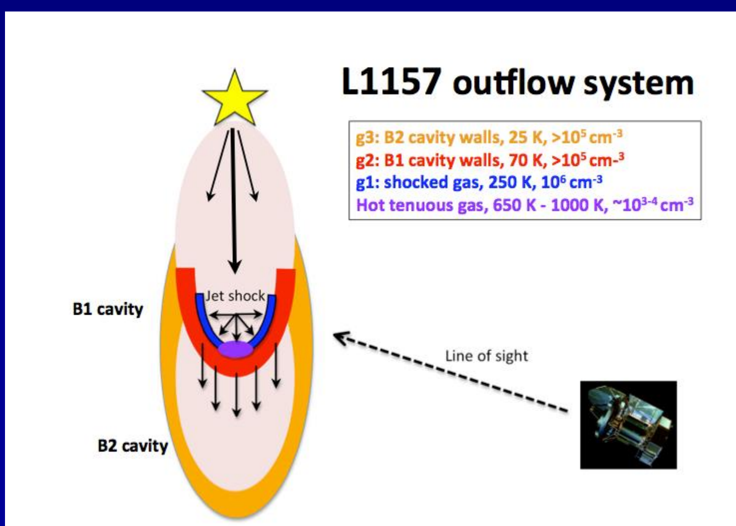


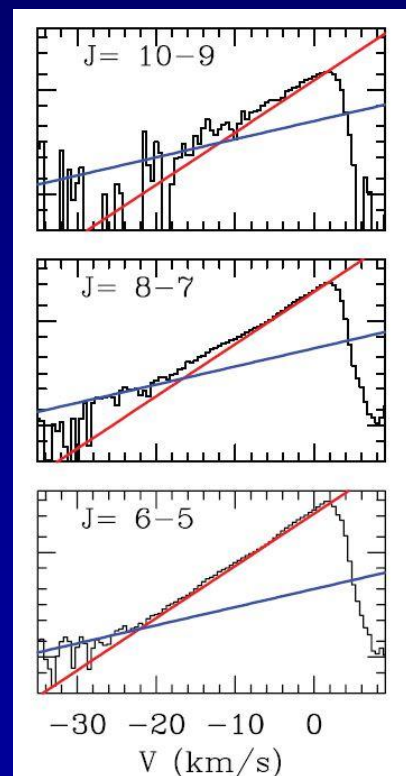
High-J CO PACS lines only prominent for compact AGNs

Loenen et al. 2010
Hailey-Dunsheath et al. 2012

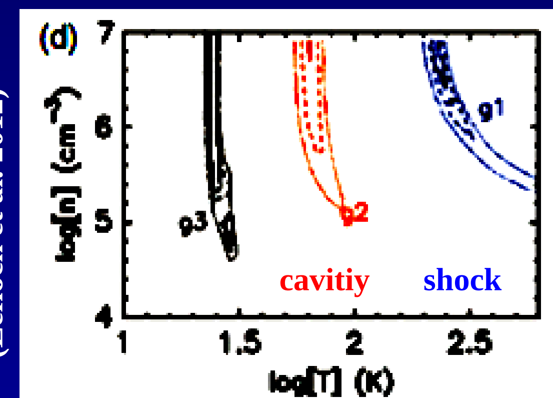
Multiple shocks revealed by high-*J* CO

- The jet impact on the cavity (Mach disk) upstream of the bow, associated with a hydrodynamical shock
- The cloud shock (bow), associated with a magnetized shock





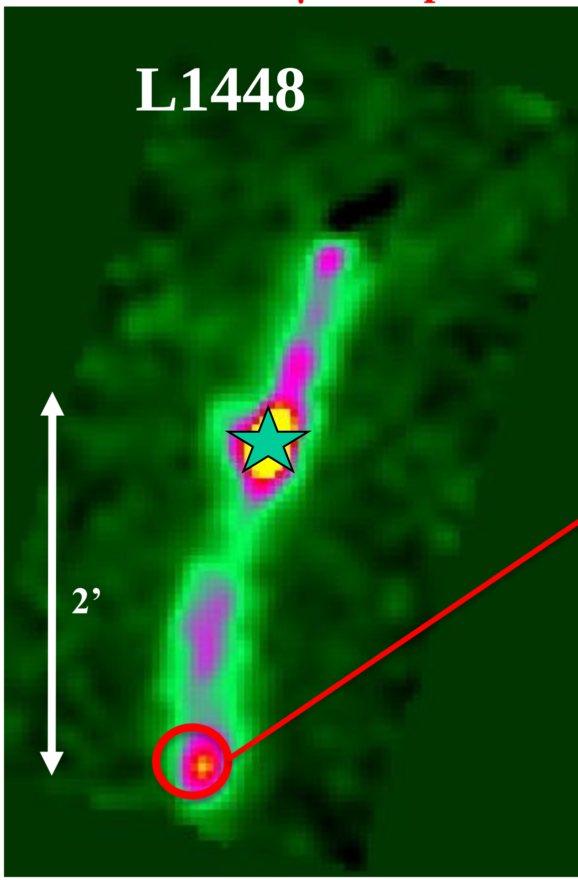
(Lefloch et al. 2012)



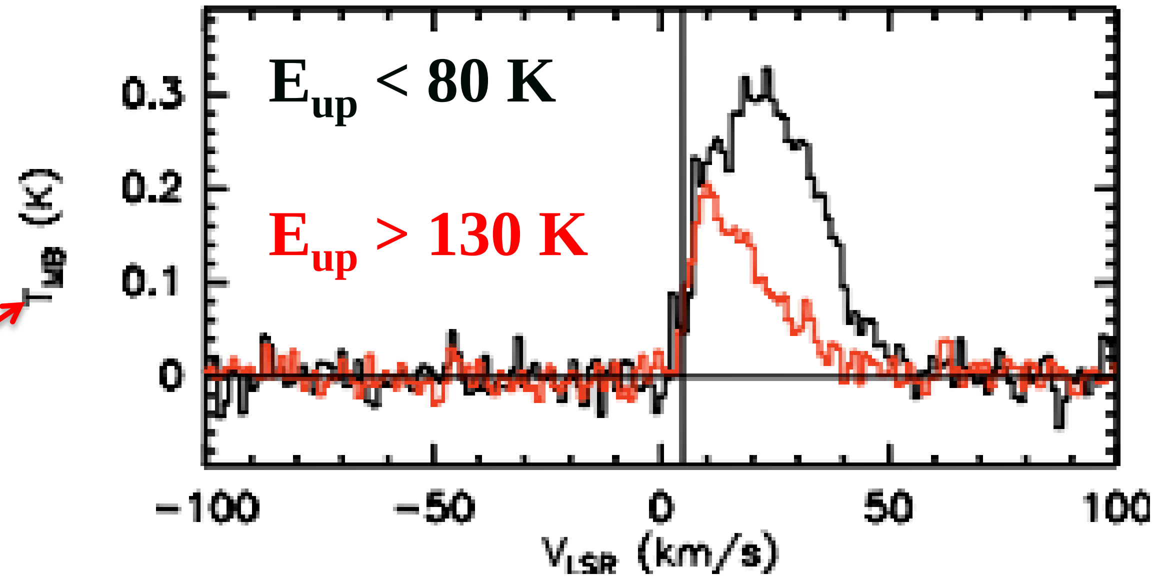
Busquet, Lefloch, Benedettini et al. 2013

Shocking water lines

PACS 179 μm map



L1448 R4 Water



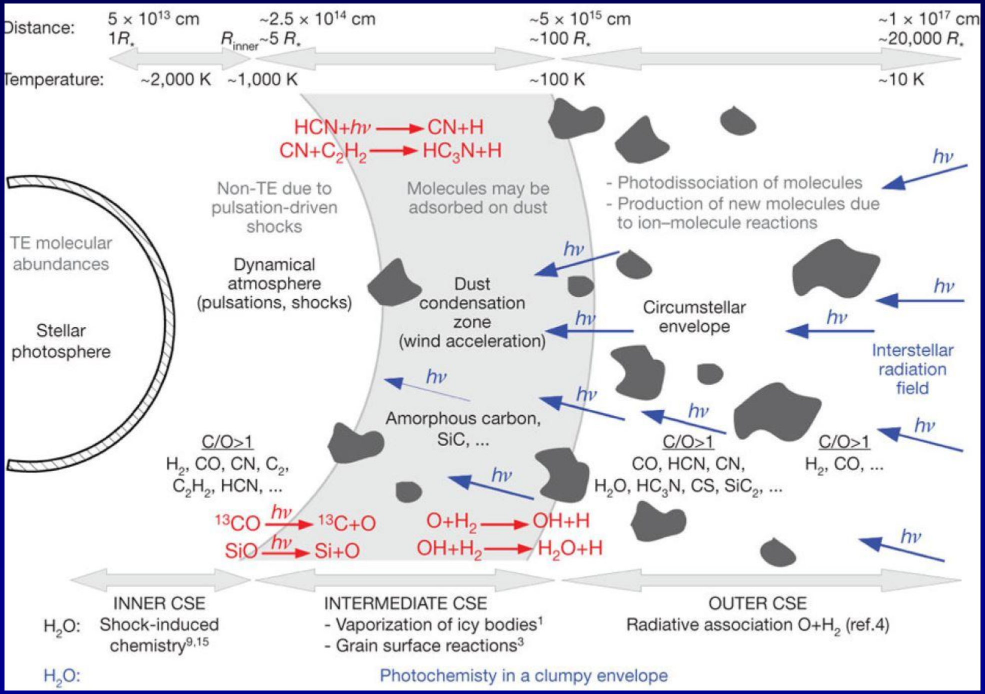
Santangelo et al. 2012
Nisini et al. 2010, Tafalla et al. 2013
LeFloch et al. 2010, Codella et al. 2010

-High-*J* CO and H_2O go together, not low-*J* CO

- Typical H_2O abundances 10^{-7} – few x 10^{-5}

New type of UV irradiated shocks? See talk Michael Kaufman

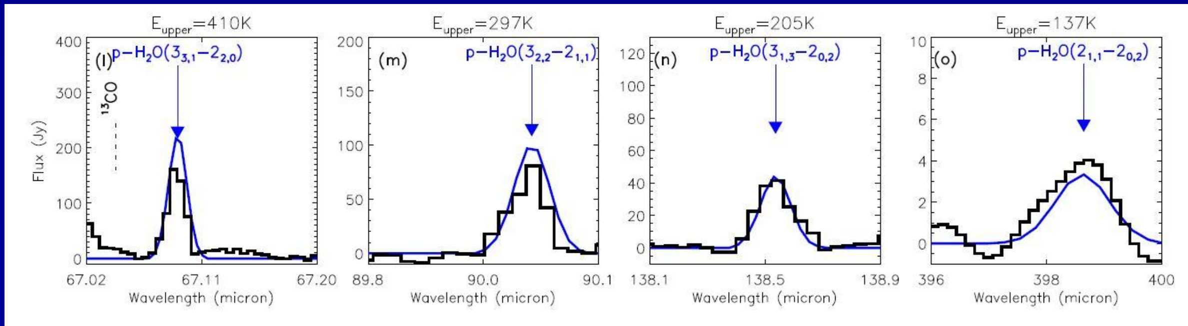
Hot water in C-rich AGB stars



- Water not due to evaporating comets

- Likely due to photodissociation of CO in clumpy envelope liberating O

Decin et al. 2010, PACS
Neufeld et al. 2011, HIFI

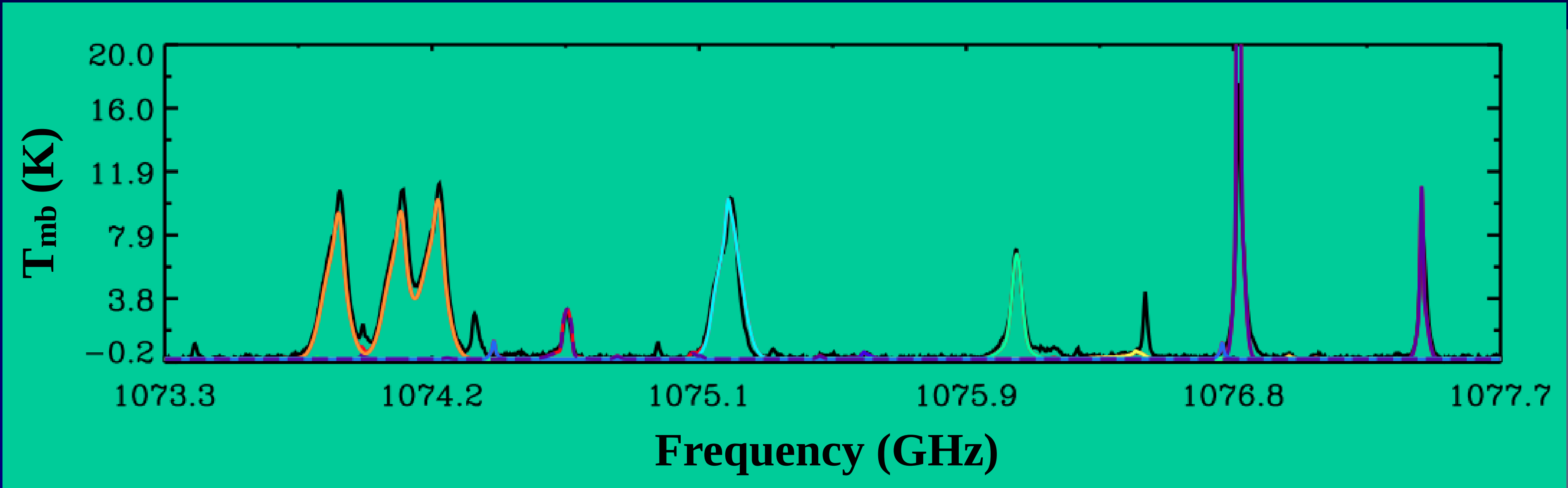


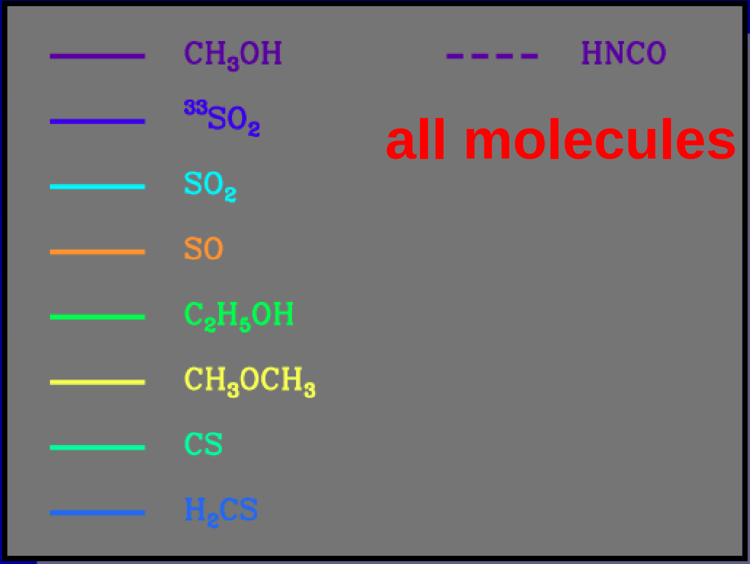
Full HIFI line surveys

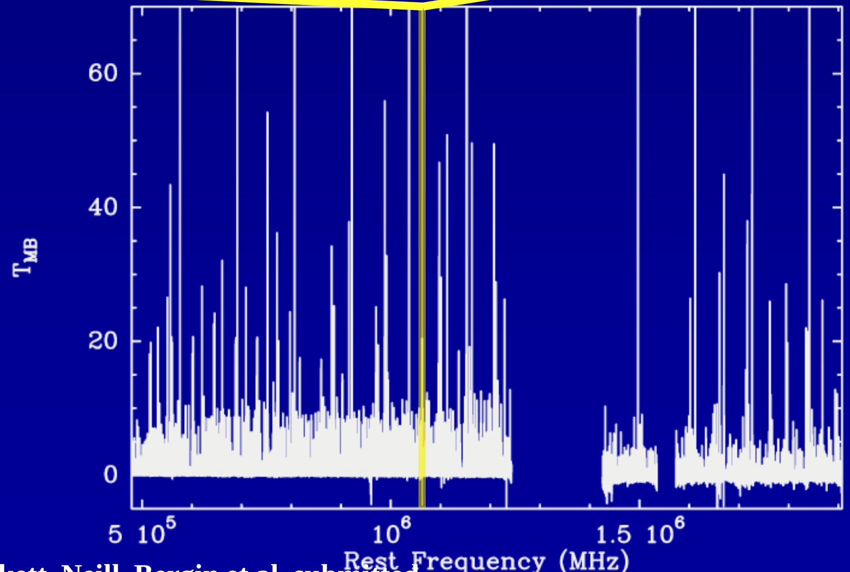
- Thousands of lines in line-rich sources
- Fraction of U-lines ~10%
- Highly excited lines of (complex) organic molecules and isotopologs
  - No new complex organics molecules
    - OK, complex species better found at lower frequencies
  - Complete inventory of which molecule ‘lives’ in which type of gas

HIFIStars HssO HEXOS CHESS

Identifying and modeling emission

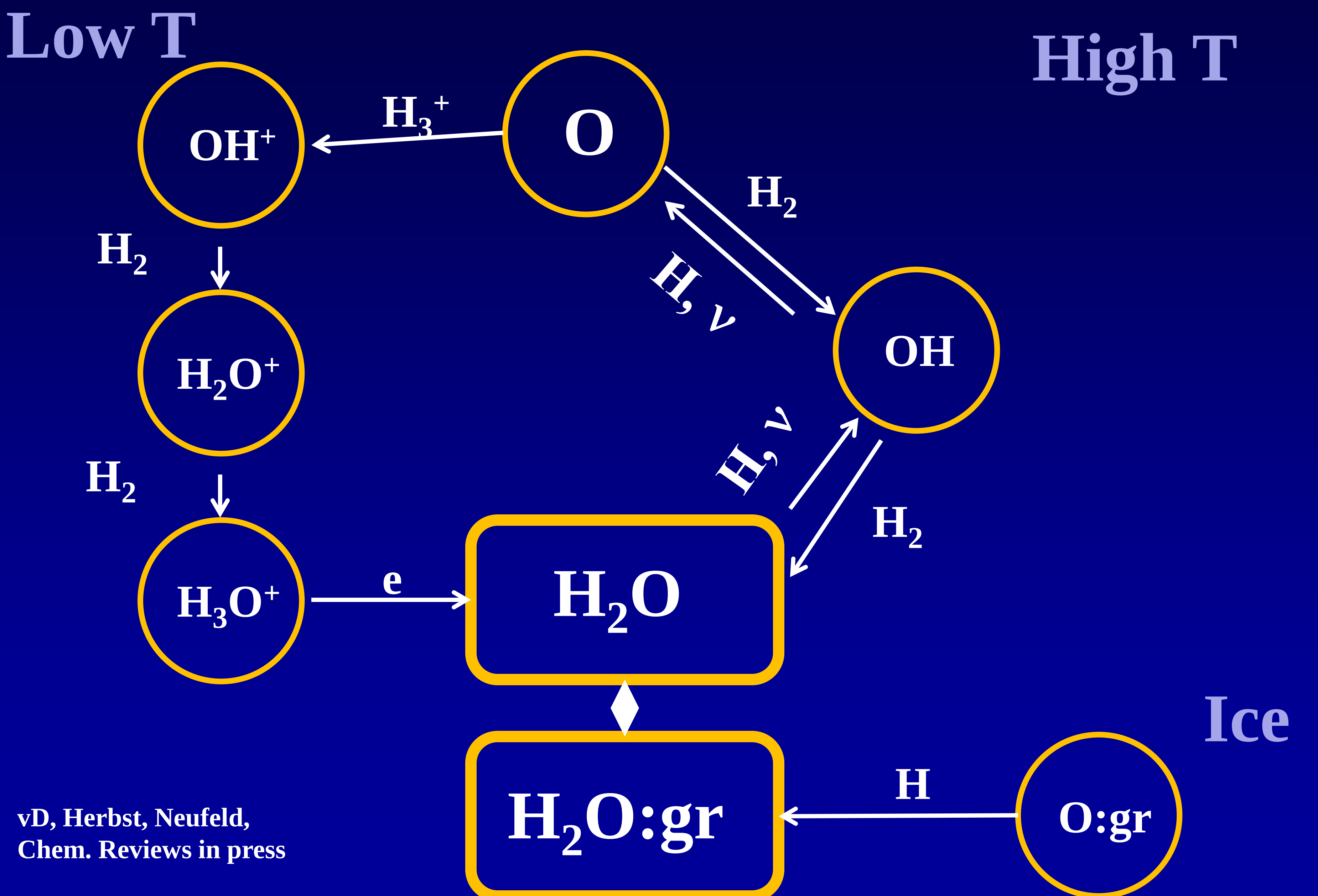






Crockett, Neill, Bergin et al. submitted

Ice chemistry

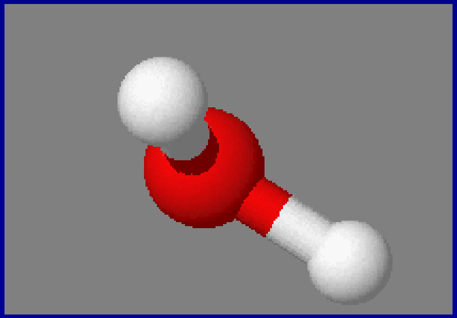


vD, Herbst, Neufeld,
Chem. Reviews in press

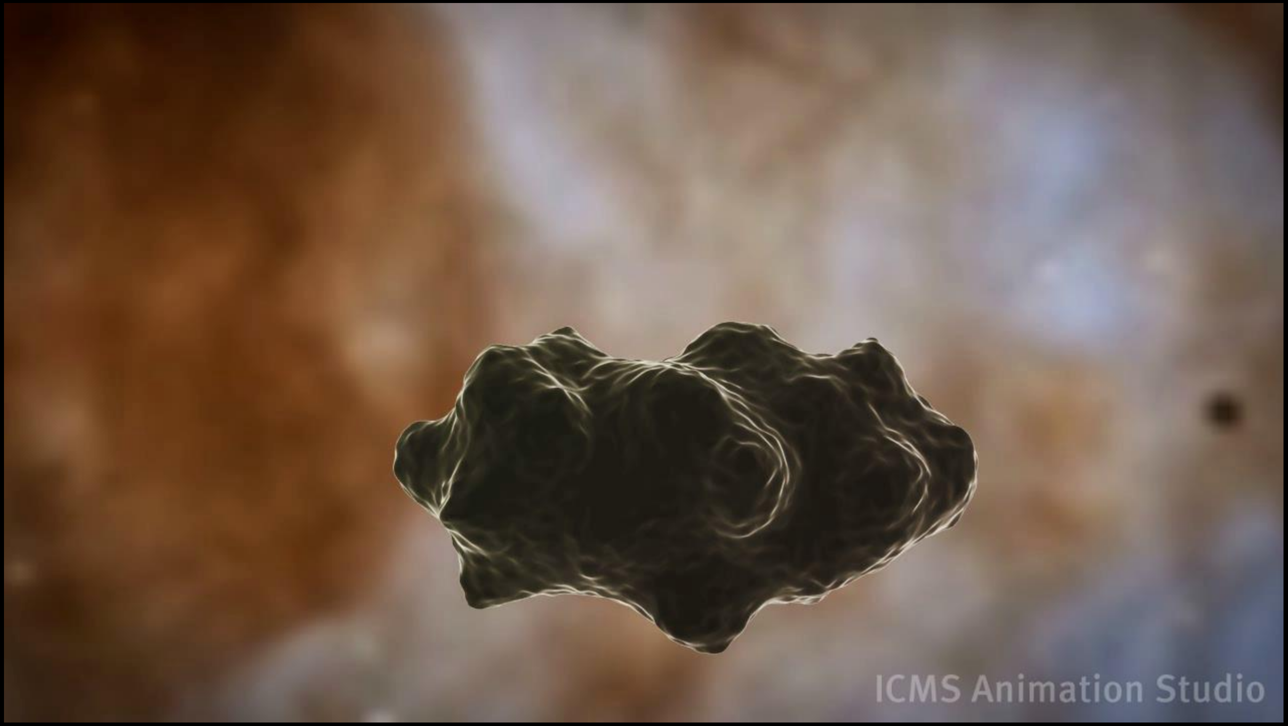
Water

- **Where is water formed in space and by which processes?**
  - **Gas vs grains**

- **What is the water 'trail' from clouds to planets?**
  - **Origin of water on Earth**



Formation of water on grains



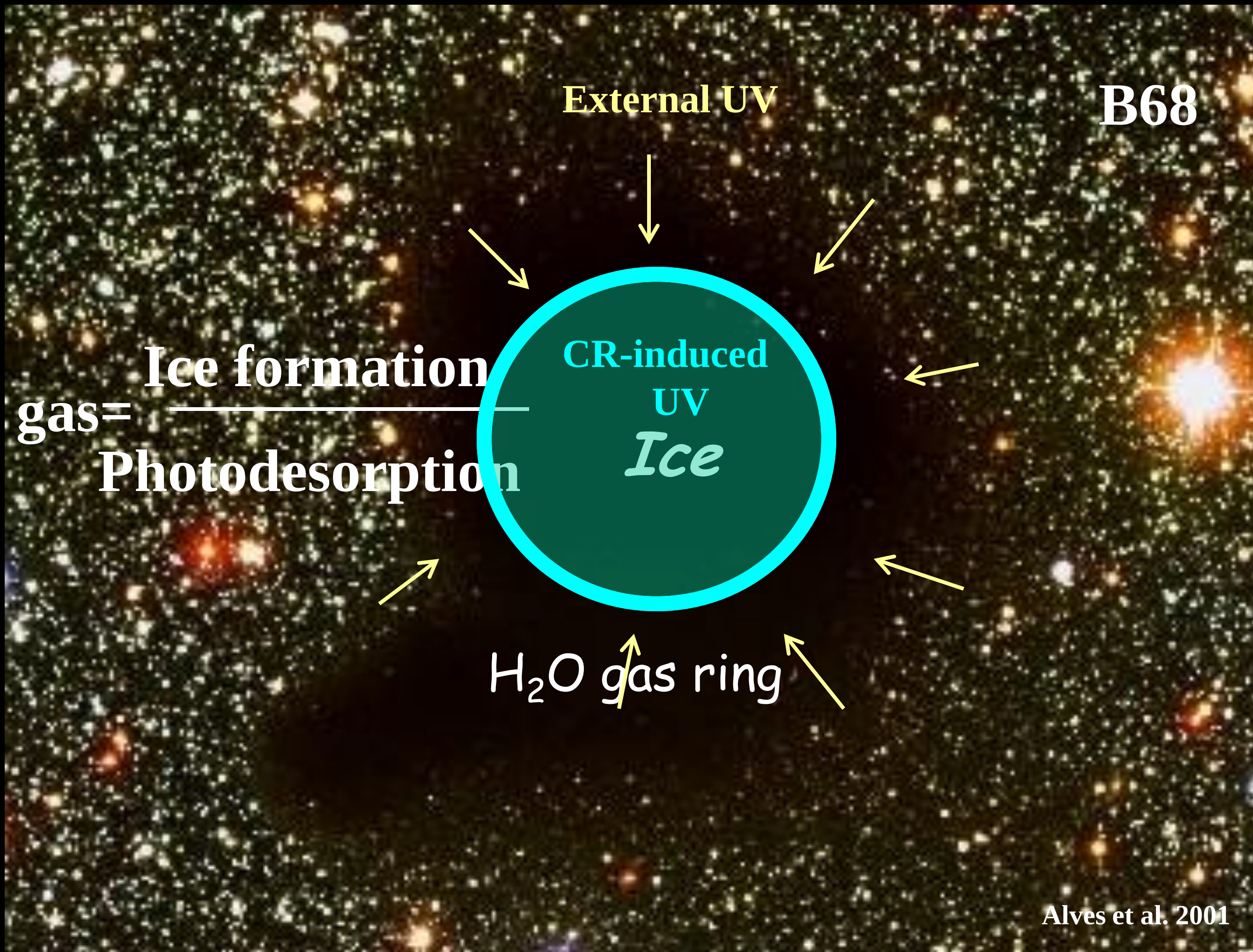
Based on Tielens & Hagen 1982
Cuppen & Herbst 2007
Cuppen et al. 2010

Based on many laboratory experiments

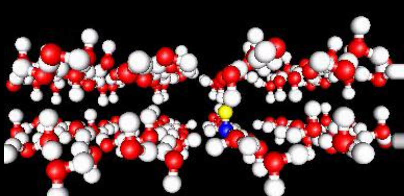
Movie will be posted late 2013 at www.strw.leidenuniv.nl/~ewine

Pre-stellar cores: where is gas-phase water?

$$H_2O \text{ gas} = \frac{\text{Ice formation}}{\text{Photodesorption}}$$



Hollenbach et al. 2009
Caselli et al. 2012



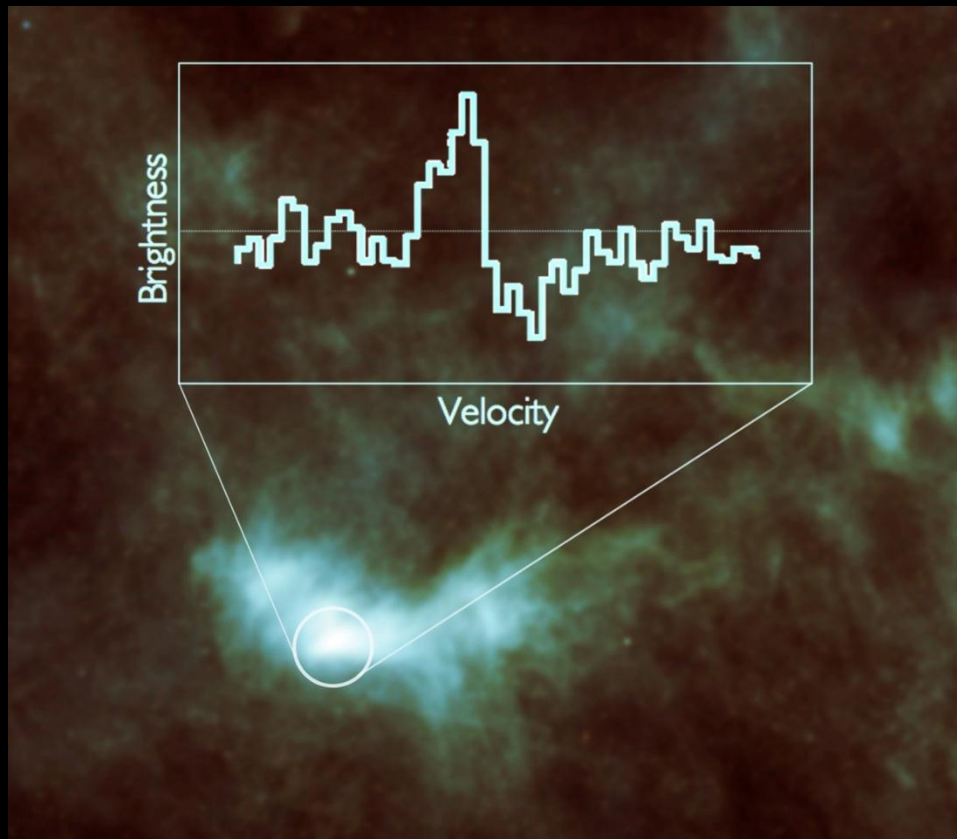
Lab + Theory

Andersson&vD2008
Öberg et al. 2009

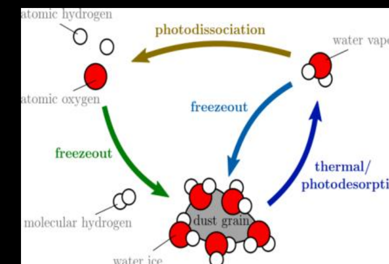
n=2.10^4 – 5.10^6 cm^{-3}, *T*=10 K

Layer of water gas where ice is photodesorbed

Detection of cold water reservoir in pre-stellar cores



ESA Sci-Tech

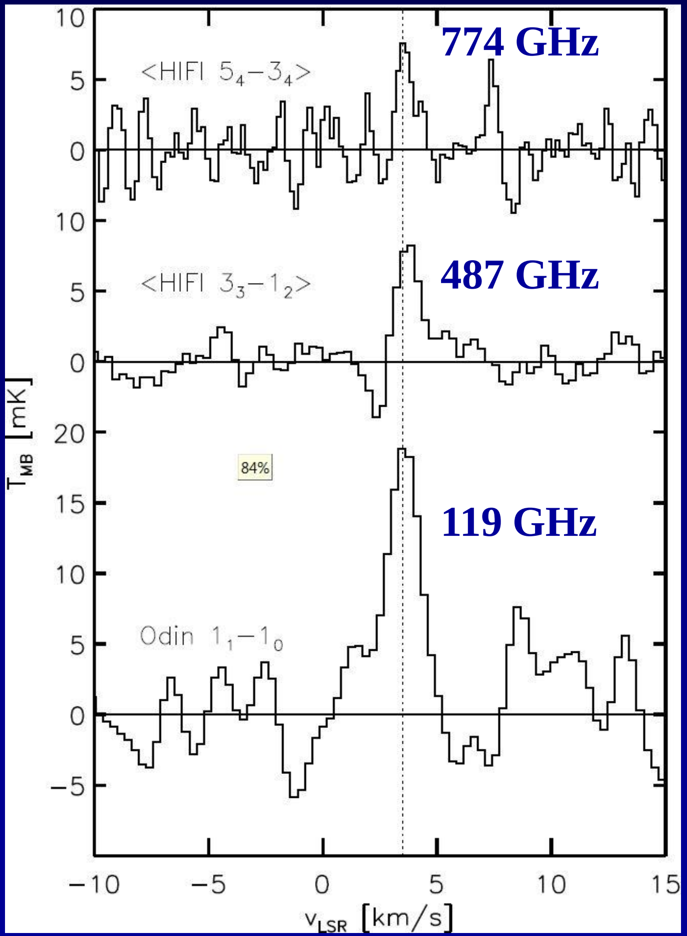


Hollenbach et al. 2009
Keto et al., Schmalzl et al.

- Simple ice chemistry works
- High density required for emission

Caselli et al. 2012

Multiline detection of O_2

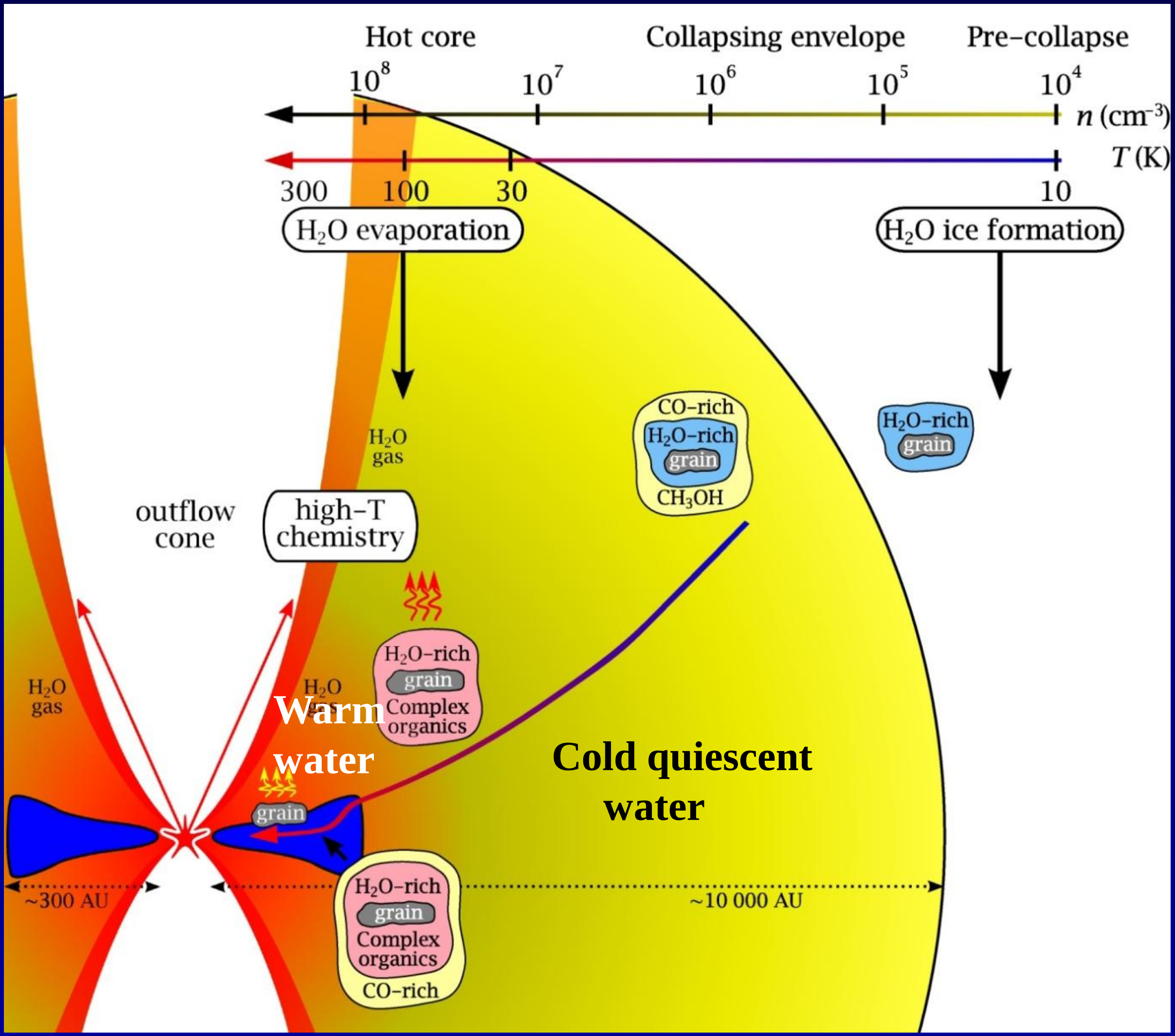


$O_2/H_2=5x10^{-8}$

- Most O and O_2 converted to H_2O
- O_2 only detected when grains warm enough to prevent O freeze-out

Liseau et al. 2012 Oph
Goldsmith et al. 2011 Orion
Yildiz et al. 2013 NGC 1333 I4A

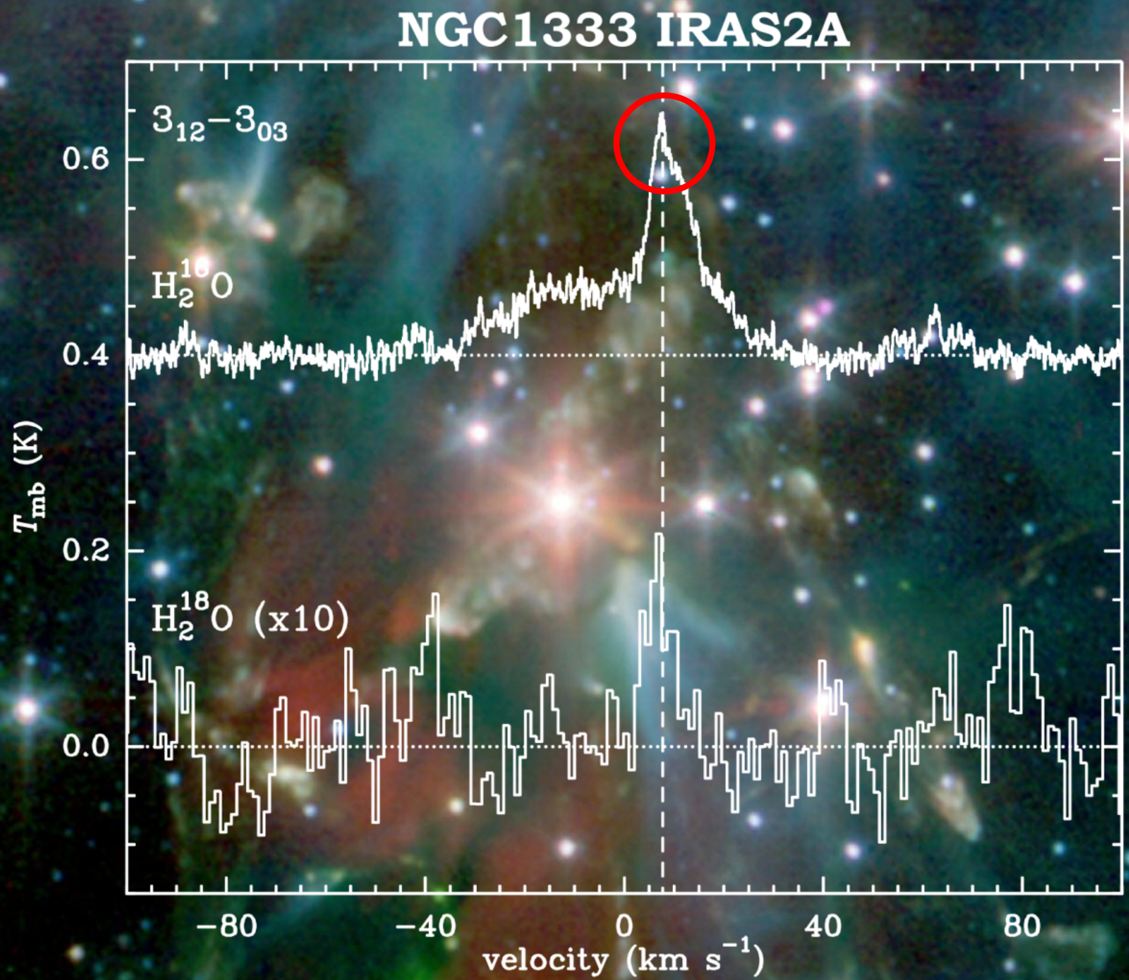
How much water is where?



Expect high water abundance in 'hot core'

Visser et al. 2009
Herbst & vD 2009

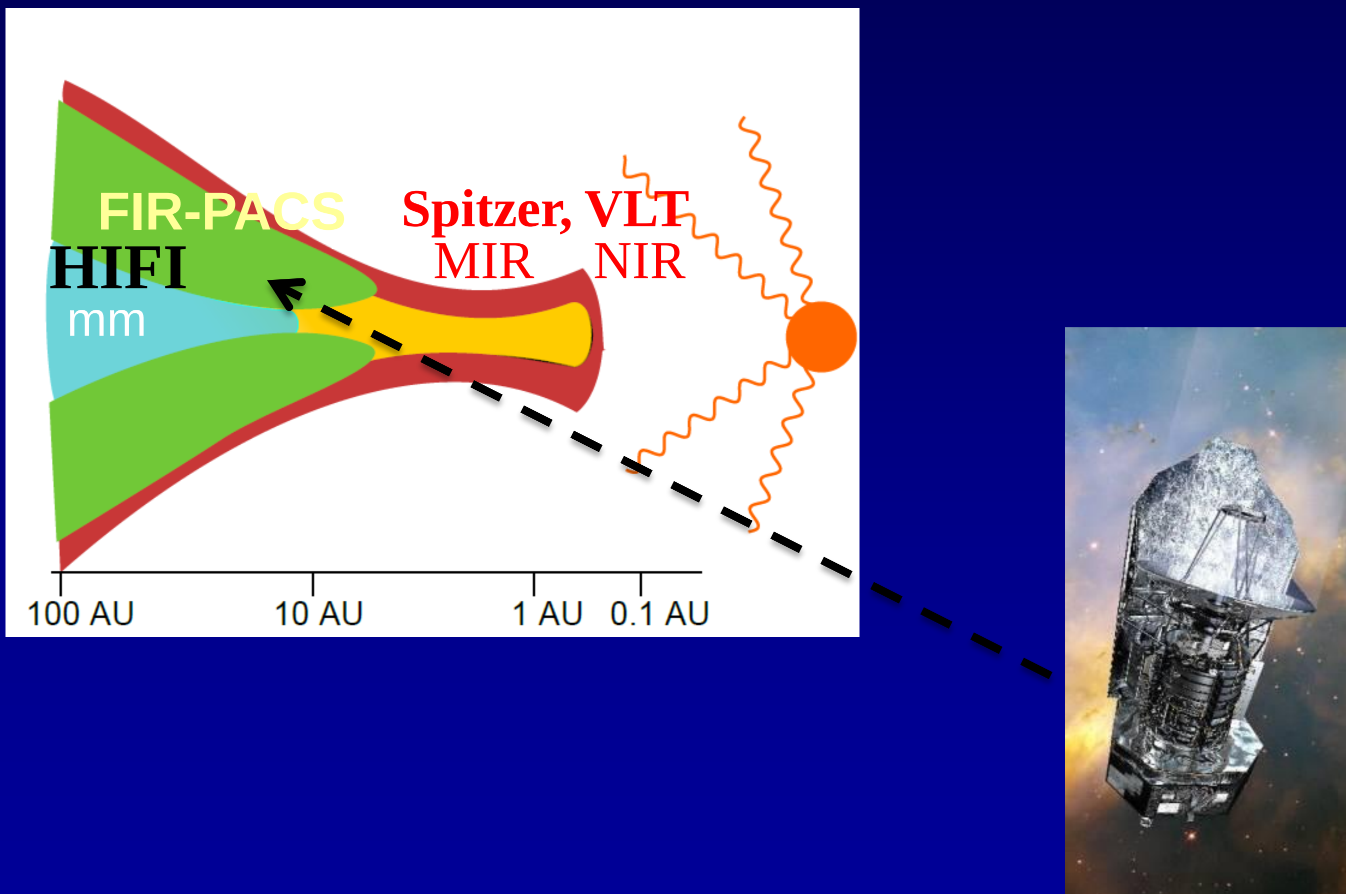
How ‘wet’ is the hot core?



Visser et al. 2013
Herpin et al. 2012
Emprechtinger et al. 2013
....

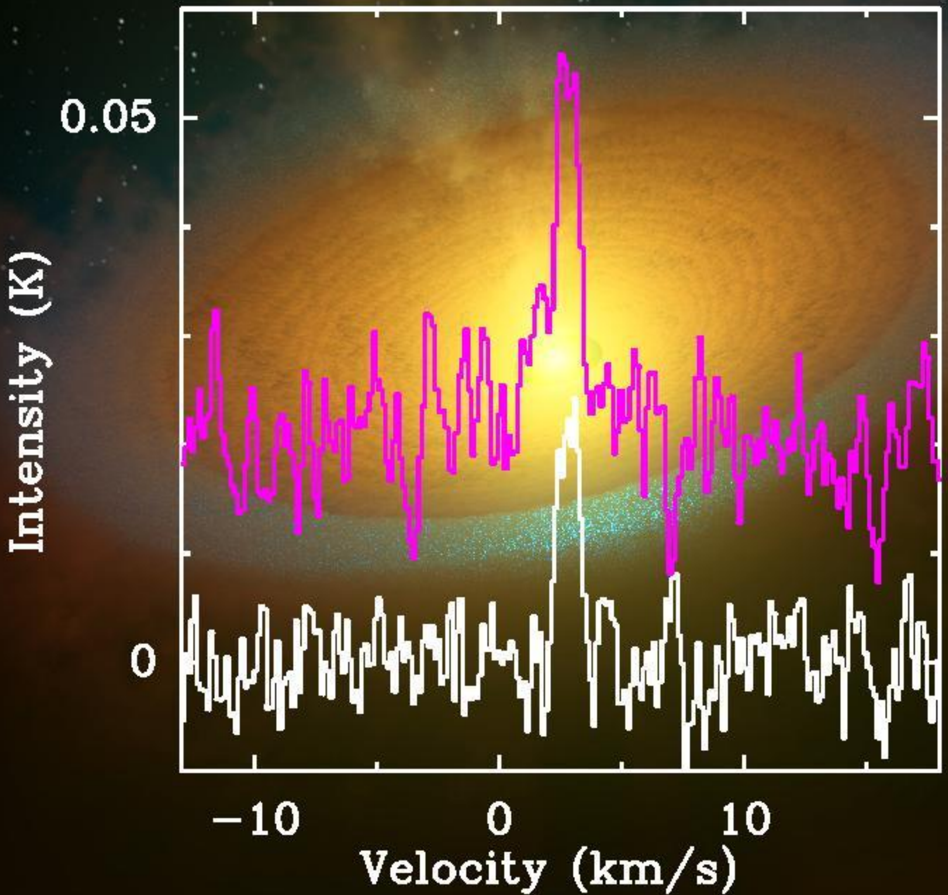
- Need isotopologs $H_2^{18}O$ to detect *narrow* emission from quiescent hot core
- Inner abundances range from 10^{-6} to 10^{-4} for low and high-mass protostars, not yet understood

Probing H_2O across the entire disk surface



D. Fedele

Revealing the cold water reservoir in disks



p-H_2O 1_{11}-0_{00}
1113 GHz

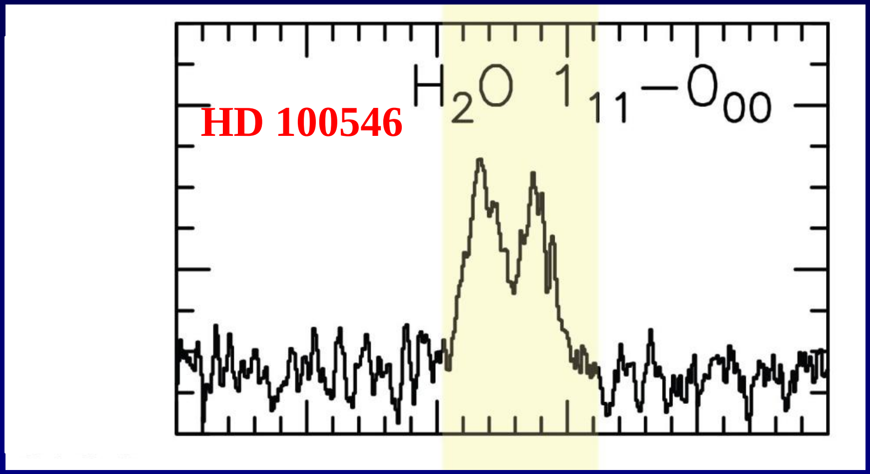
o-H_2O 1_{10}-1_{01}
557 GHz

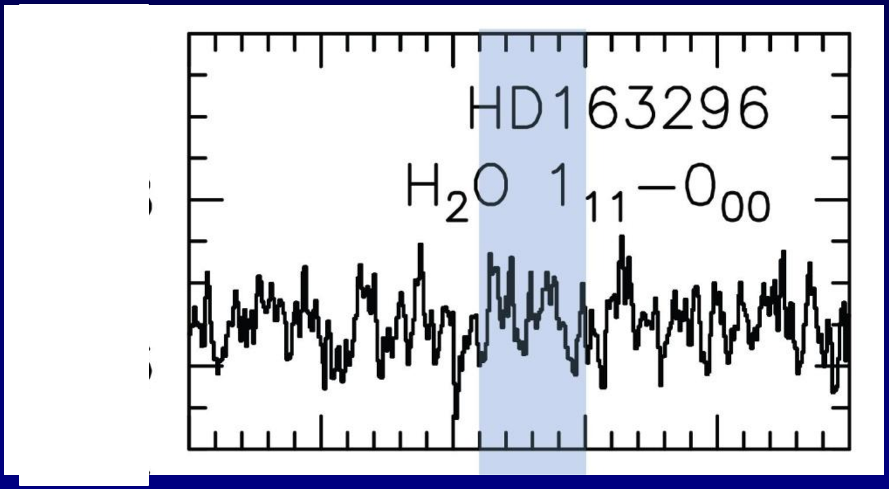
o/p <1

Hogerheijde et al. 2011, Science

Detection points to 6000 oceans of water ice

Water in disks survey





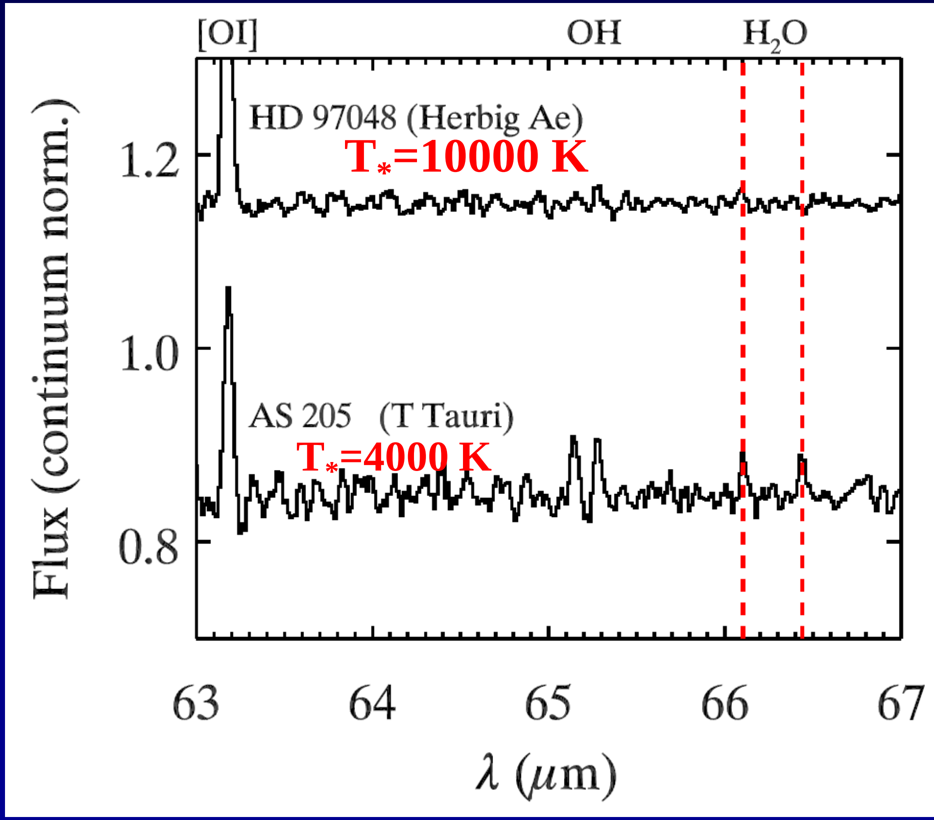
Hogerheijde et al., in prep.

- Firm detections in 2 disks
  - o/p<1 unless gas does not follow dust
  - + DG Tau special case (late Class I, outflow?) Podio et al. 2013
- No detections in other disks in spite of very deep obs

Absence of cold water emission is common feature

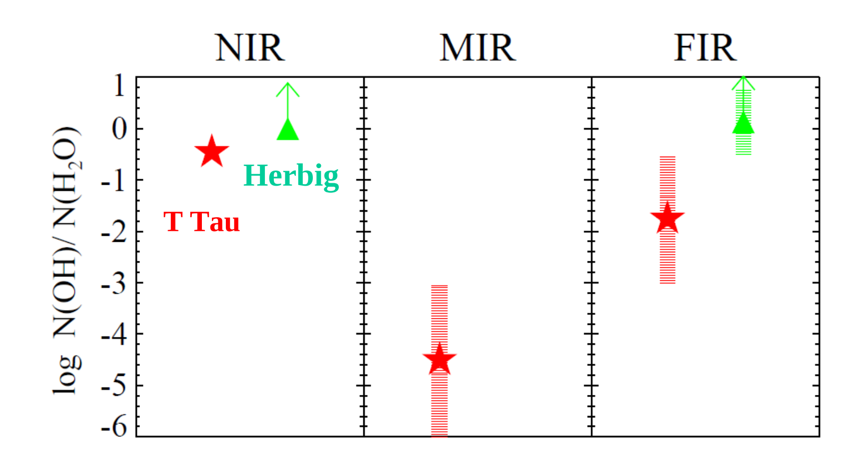
Models:
Bergin et al.,
Woitke et al.
Kamp et al.
……

PACS survey H_2O



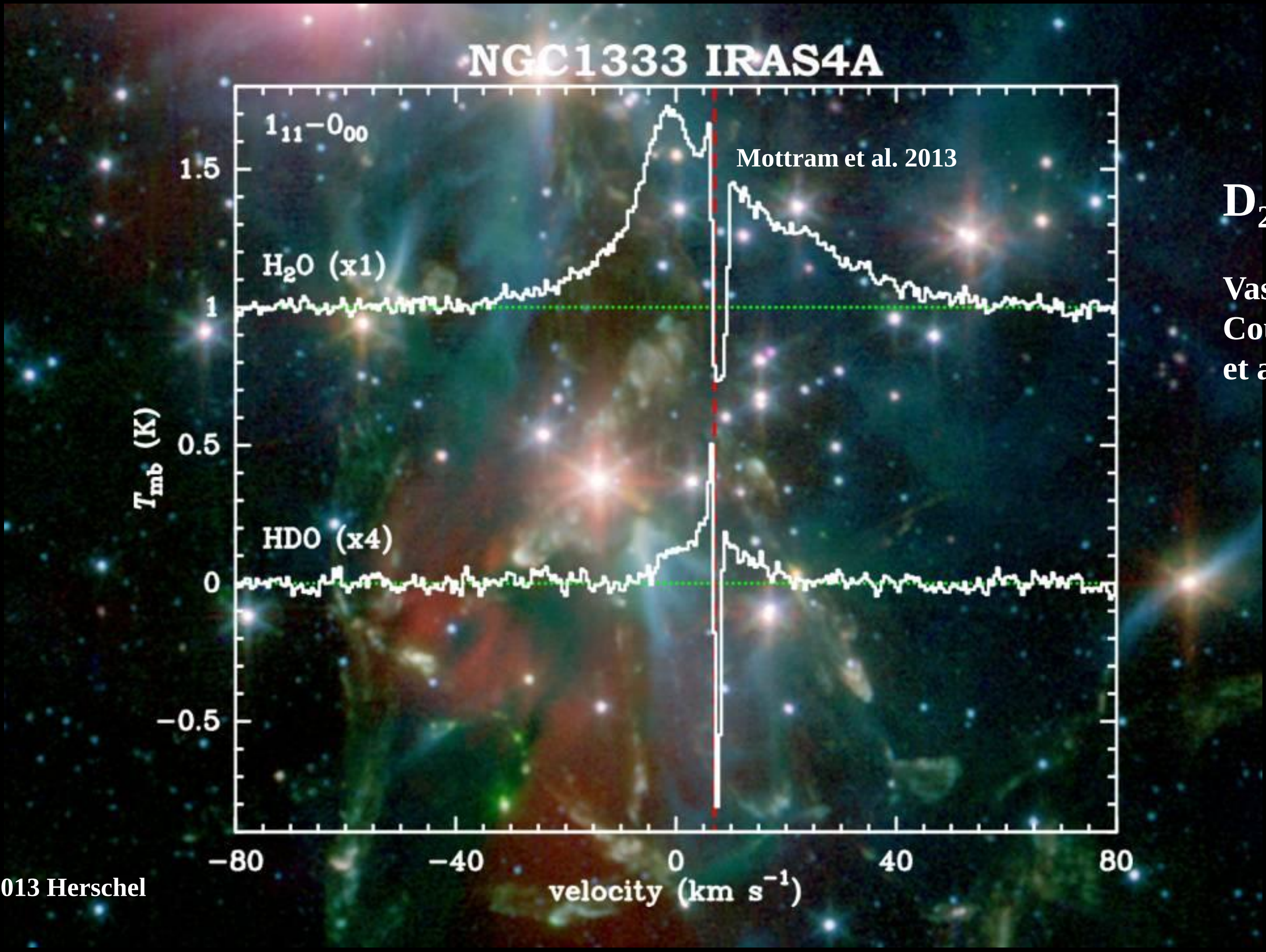
- Far-IR H_2O detected in T Tau disks, but hardly in Herbig disks

$$H_2O + h\nu \rightarrow OH + H$$



Fedele, Meeus et al. 2012, 2013
Salyk et al. in prep.
Riviere-Marichalar et al. 2012, GASPS
Zhang et al. 2013

HDO/H_2O: high or low?



D_2O

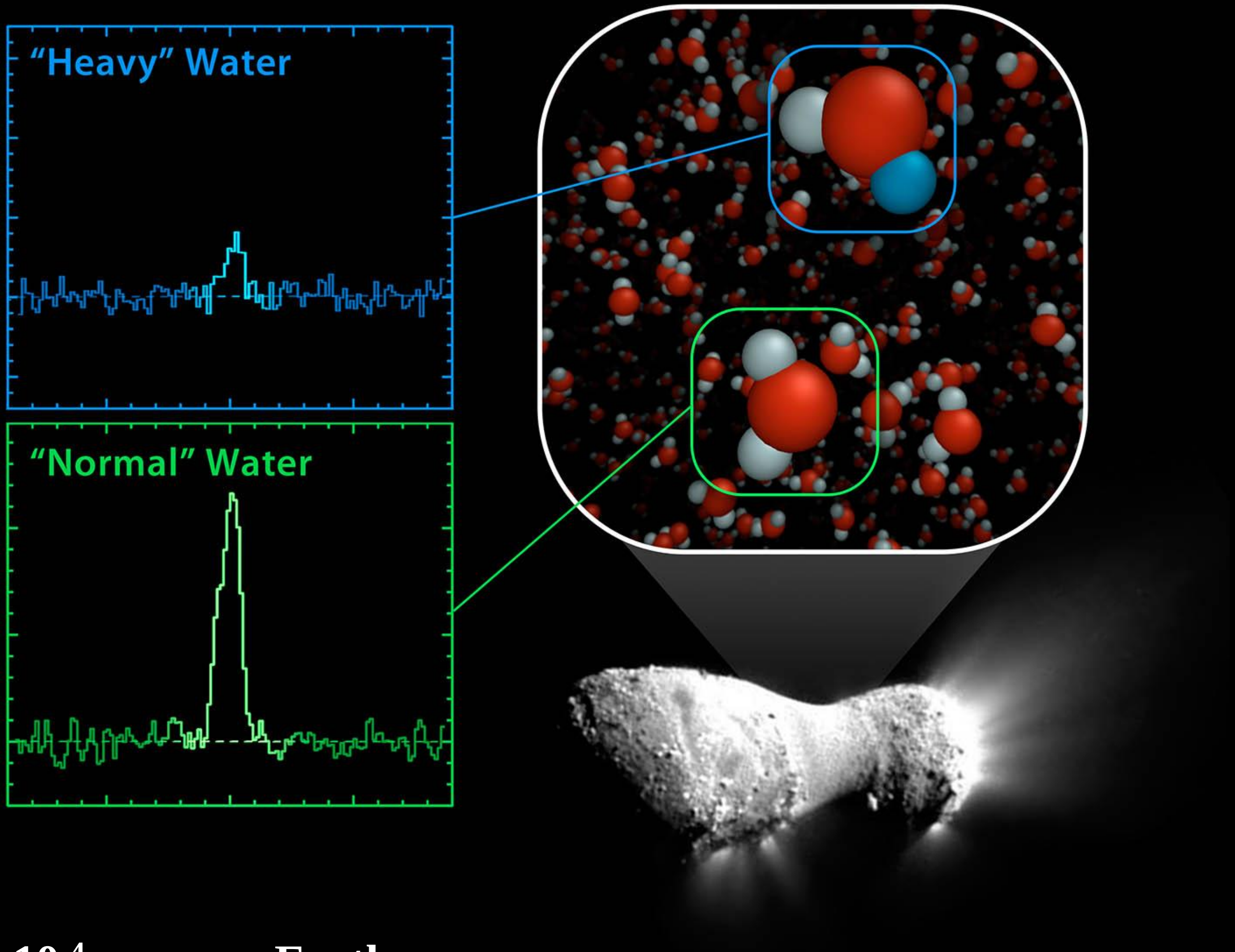
Vastel, Coutens et al.

Coutens et al. 2012, 2013 Herschel
Visser et al. 2013

Persson et al. 2012, 2013 IRAM/ALMA

Optical depth $H_2^{18}O$ lines higher than thought before
Recent analyses agree on warm HDO/H_2O = (0.5-1)x10^{-3}

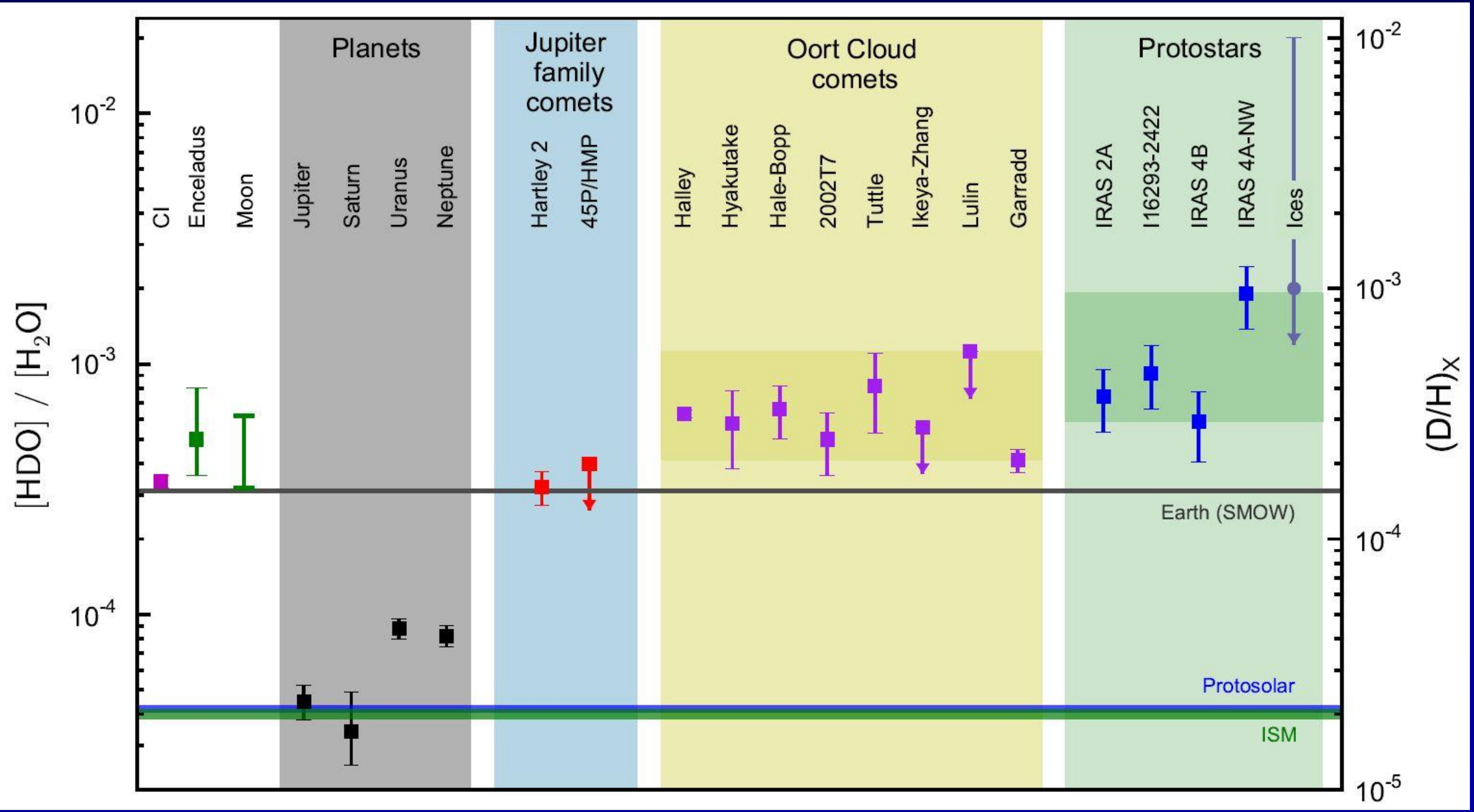
HDO/H_2O in Jupiter family comet



HDO/H_2O=3x10^{-4}, same as Earth oceans

Hartogh, Lis et al. 2011, Nature

HDO/H_2O as tracer of origin of Earth's water

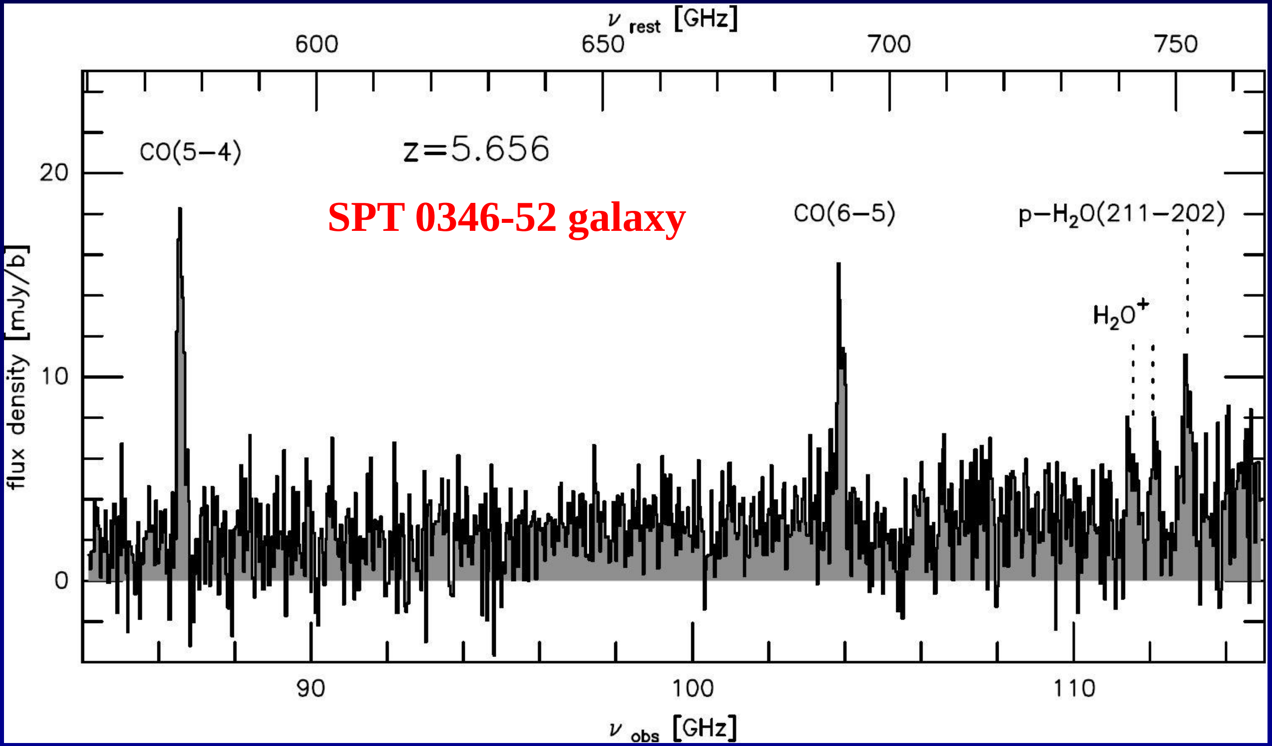


Persson et al. 2013, submitted

Summary

- Hydrides
  - Precision astrochemistry
  - Diagnostics of H_2, ζ, turbulence, ….
  - State specific chemistry and excitation
- Line surveys
  - Origin complex organic molecules
  - Legacy
- High temperature chemistry
  - Hot CO and H_2O in shocks, CO ladder
  - Importance of irradiated shocks
- Water and O_2
  - Trail from cores to disks
- Setting the scene for extragalactic chemistry, out to high z

From Herschel to ALMA



Weiss et al. 2013
ALMA

Astrochemistry is everywhere throughout the Universe!

The promise of Herschel is being delivered

Thanks to instrument teams for making this possible!