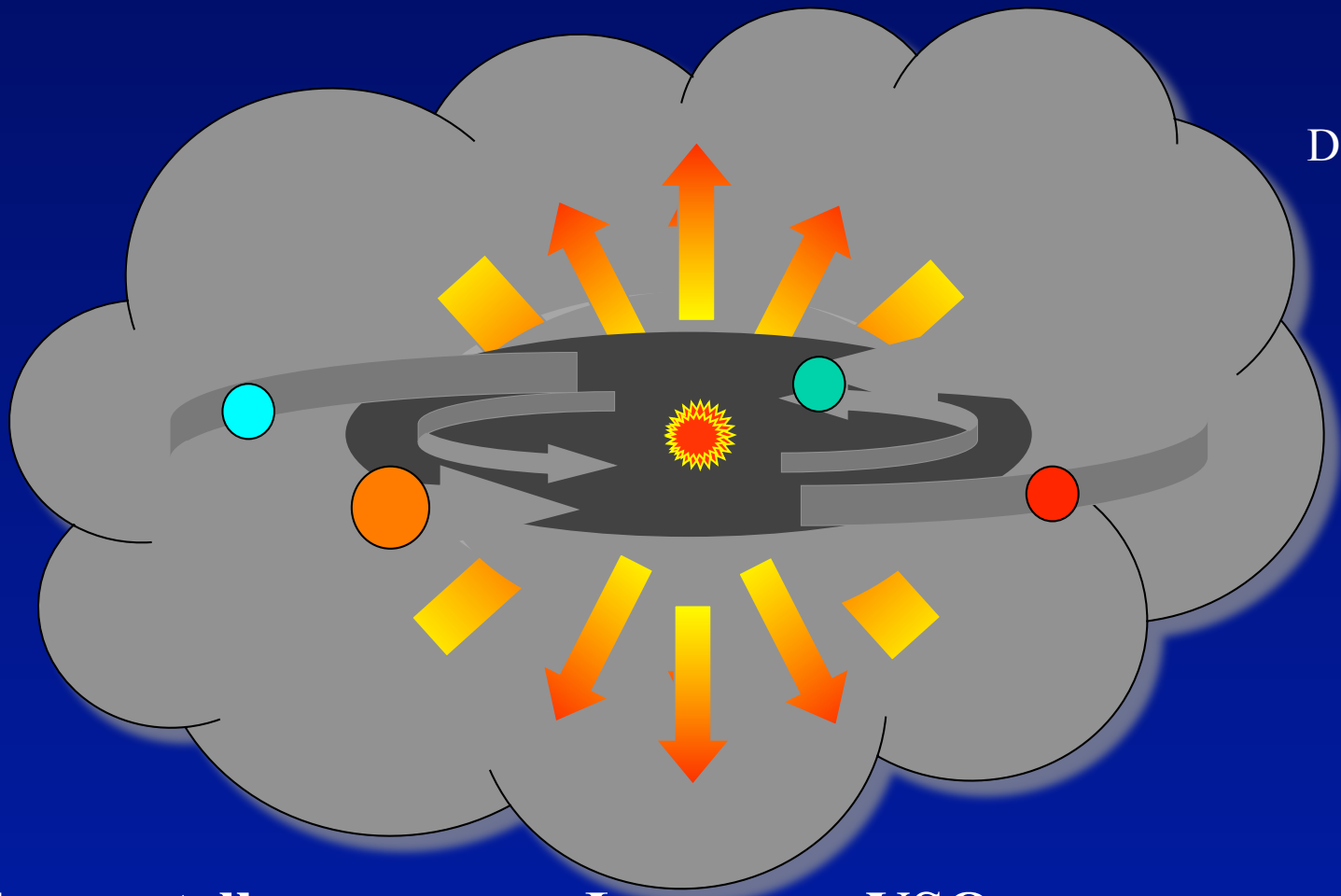
Water In Star-forming regions with Herschel

- A 429 hr GT key-program with Herschel to study the physical and chemical structure of star forming regions focussing on H_2O and its related species
- Program covers ~90 sources ranging from pre-stellar cores, low- to high-mass protostars in different evolutionary stages as well as protoplanetary disks
- Both HIFI and PACS-spectroscopy are used
  - Includes small maps up to ~2'x2'
- Collaboration of ~70+ scientists from 30 different institutes

See http://www.strw.leidenuniv.nl/WISH

Follow water trail during star and planet formation



D. Lommen

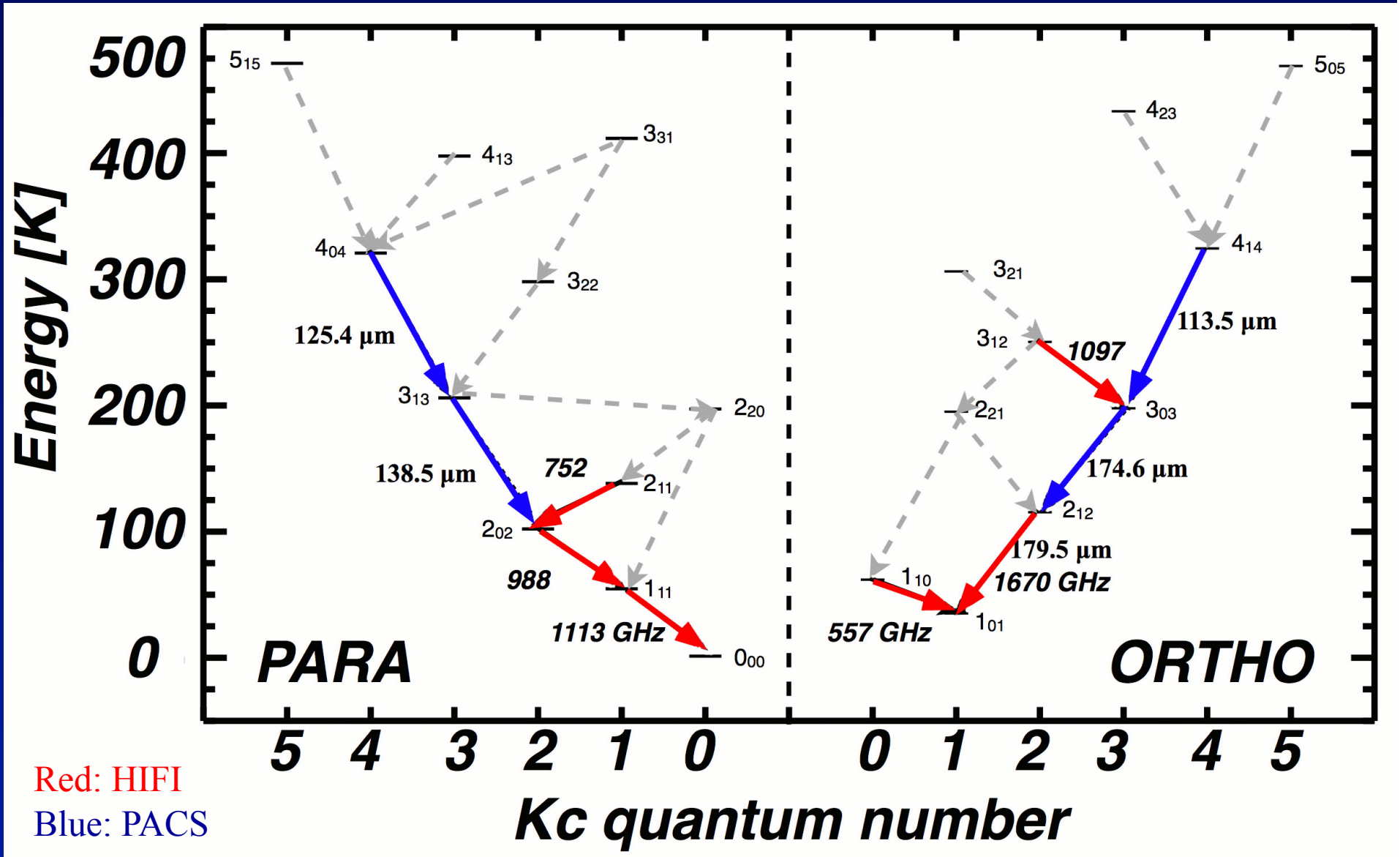
Dark pre-stellar cores → Low-mass YSOs → Disks
Infrared dark clouds Intermediate mass YSOs
High-mass YSOs

Why water?

- H_2O abundance shows large variations in SF regions: $<10^{-8}$ (cold) – 3. 10^{-4} (warm) → unique probe of different physical regimes
  - Natural filter of warm gas
- Main reservoir of oxygen → affects chemistry of all other species
  - Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution
- Astrobiology: water associated with life on Earth → characterize water 'trail' from clouds to planets, including origin of water on Earth

pre-stellar cores → YSO's → disks → comets

H_2O lines: HIFI vs PACS



Red: HIFI
Blue: PACS

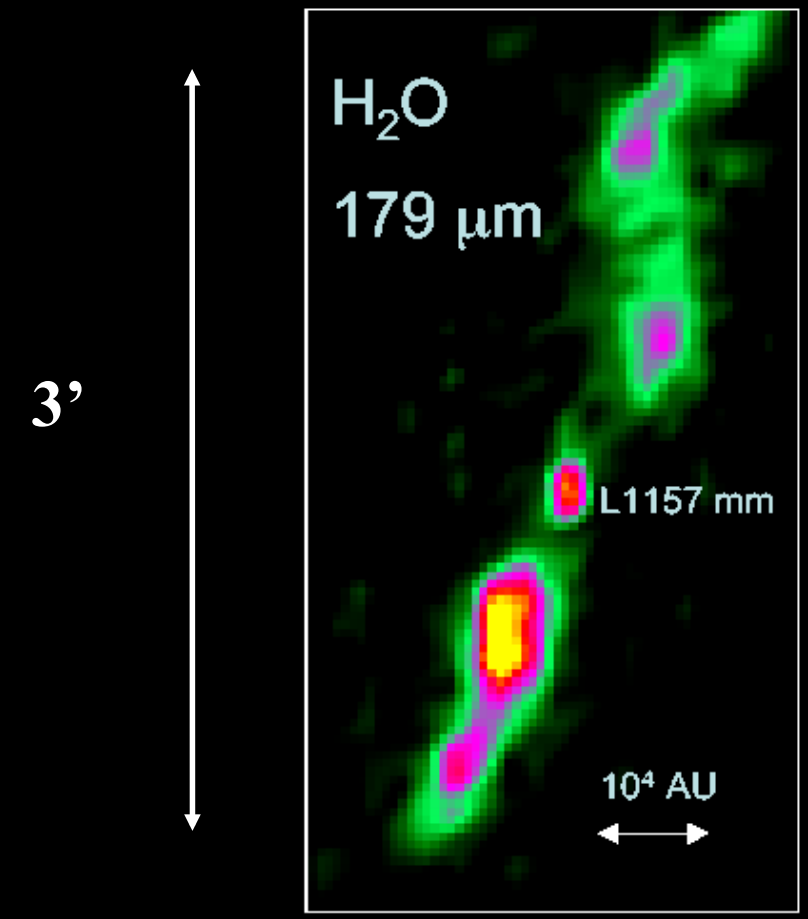
Observe mix of low- and high-excitation lines to probe cold and hot environments

First results letters submitted

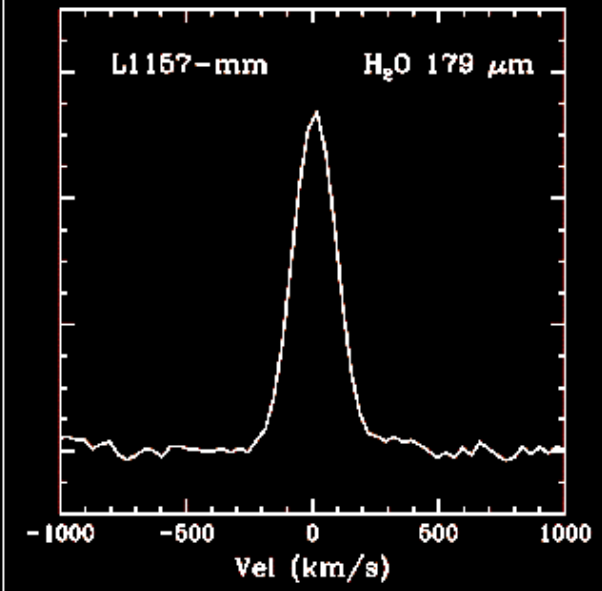
- HH 46 PACS: van Kempen, Kristensen et al.
- NGC 7129 PACS: Fich et al.
- L1157 outflow PACS: Nisini et al.
- DR 21 HIFI: van der Tak et al.

Highlight

Herschel-PACS image of water in proto-stellar systems



L1157-mm outflow
D = 440 pc, L_{bol} = 11 L_o



Nisini, Liseau, Tafalla, Benedettini et al.

Water traces ‘hot spots’ where shocks dump energy into cloud

SDP/PSP HIFI data received

- Pre-stellar cores: B68, L1544
- Low-mass YSOs:
  - NGC 1333 I2A, I4A, I4B: many lines but 557 GHz not taken
  - Other sources: 557 GHz only
- Outflows: *none*
- Intermediate mass: NGC 7129 some lines
- High mass: some SDP/PSP sources
- Rad. diagnostics: W3 IRS5
- Disks: deep DM Tau, shallow: BP Tau, HD163296, AS209

Problems?

- Instrumental
  - Some minor issues
  - Otherwise data quality ‘perfect’ (rms close to expected)
  - Waiting for mapping mode release
- Scheduling
  - Random: some sources observed in some lines, others in others → difficult to get consistent set of lines even for small sample of sources
    - several SDP and PSP-1 not executed before sources disappeared from visibility
- Software
  - Some use HIPE, most use CLASS
  - Automatic data pipeline produces good quality data + CLASS files: WISH Live data show (thanks to Umut Yildiz + Erik Deul)

WISH-team

- ***E.F. van Dishoeck,*** **Y. Aikawa, R. Bachiller, A. Baudry, M. Benedettini,** ***A. Benz,*** **E. Bergin, P. Bjerkeli, G. Blake, S. Bontemps, J. Braine, A. Brandeker, S. Bruderer,** ***P. Caselli,*** **J. Cernicharo, L. Chavarria, C. Codella, F. Daniel, C. Dedes, P. Encrenaz, A.M. di Giorgio, C. Dominik, S. Doty, H. Feuchtgruber, M. Fich, W. Frieswijk, A. Fuente, T. Giannini, J.R. Goicoechea, Th. De Graauw, F. Helmich,** ***F. Herpin,*** **G. Herczeg,** ***M. Hogerheijde,*** **T. Jacq, J. Jørgensen,** ***D. Johnstone,*** **A. Karska, M. Kaufman, E. Keto, L. Kristensen, B. Larsson, B. Lefloch, D. Lis,** ***R. Liseau,*** **M. Marseille, C. McCoey, G. Melnick, D. Neufeld, B. Nisini, M. Olberg, G. Olofsson, L. Pagani, O. Panić, B. Parise, J. Pearson, R. Plume, C. Risacher, D. Salter, N. Sakai, J. Santiago, P. Saraceno, R. Shipman, M. Tafalla,** ***F. van der Tak,*** **T. van Kempen, R. Visser, S. Viti, S. Wampfler, M. Walmsley, F. Wyrowski, S. Yamamoto, U. Yildiz**

(blue indicates subteam leader; yellow project scientists)

Those who did the work to make this presentation possible….

- *E.F. van Dishoeck,* Y. Aikawa, R. Bachiller, A. Baudry, M. Benedettini, *A. Benz,* E. Bergin, P. Bjerkeli, G. Blake, S. Bontemps, J. Braine, A. Brandeker, *S. Bruderer*, *P. Caselli,* J. Cernicharo, L. Chavarria, C. Codella, F. Daniel, C. Dedes, P. Encrenaz, A.M. di Giorgio, C. Dominik, S. Doty, H. Feuchtgruber, *M. Fich*, W. Frieswijk, A. Fuente, T. Giannini, J.R. Goicoechea, Th. De Graauw, F. Helmich, *F. Herpin, G. Herczeg, M. Hogerheijde,* T. Jacq, J. Jørgensen, D. Johnstone, A. Karska, M. Kaufman, E. Keto, *L. Kristensen*, B. Larsson, B. Lefloch, D. Lis, R. Liseau, M. Marseille, C. McCoey, G. Melnick, D. Neufeld, B. Nisini, M. Olberg, G. Olofsson, L. Pagani, B. Parise, O. Panić, J. Pearson, R. Plume, C. Risacher, D. Salter, N. Sakai, J. Santiago, P. Saraceno, R. Shipman, M. Tafalla, *F. van der Tak,* T. van Kempen, *R. Visser*, S. Viti, *S. Wampfler,* M. Walmsley, *F. Wyrowski,* S. Yamamoto, *U. Yildiz*

Pre-stellar cores in WISH

PLAN: observe H_2O (1_{10}-1_{01}) to measure the initial content of water vapor in star forming regions before stars are born, as a function of environmental conditions

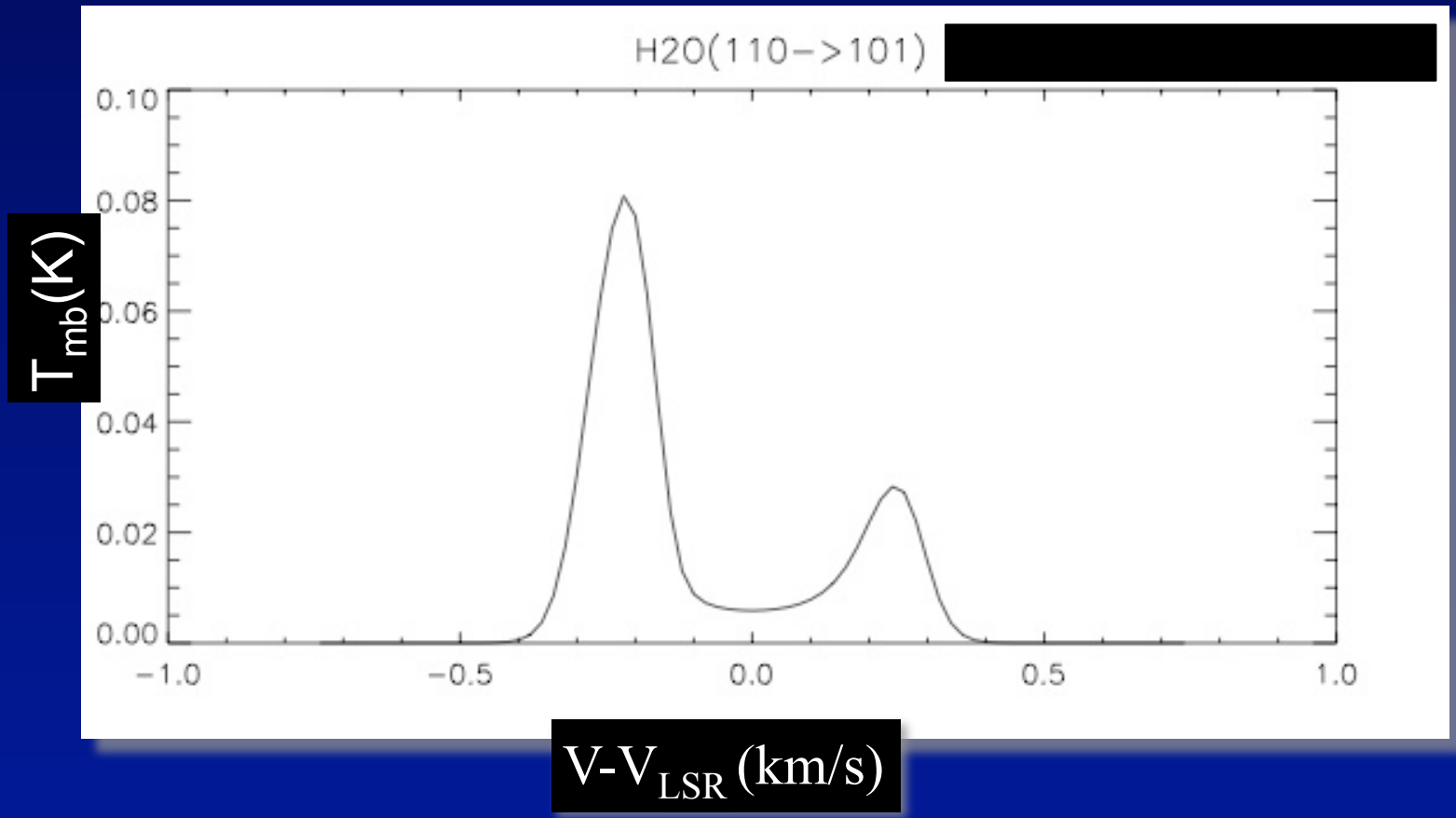
Original Total time: 20h (Italy) + 2h (Spain)

Team: Paola Caselli (leader), Yuri Aikawa, Ted Bergin, Eric Keto, Laurent Pagani, Mario Tafalla, Floris van der Tak, Malcolm Walmsley

+ *Brunella Nisini, Claudio Codella (Italian representatives)*

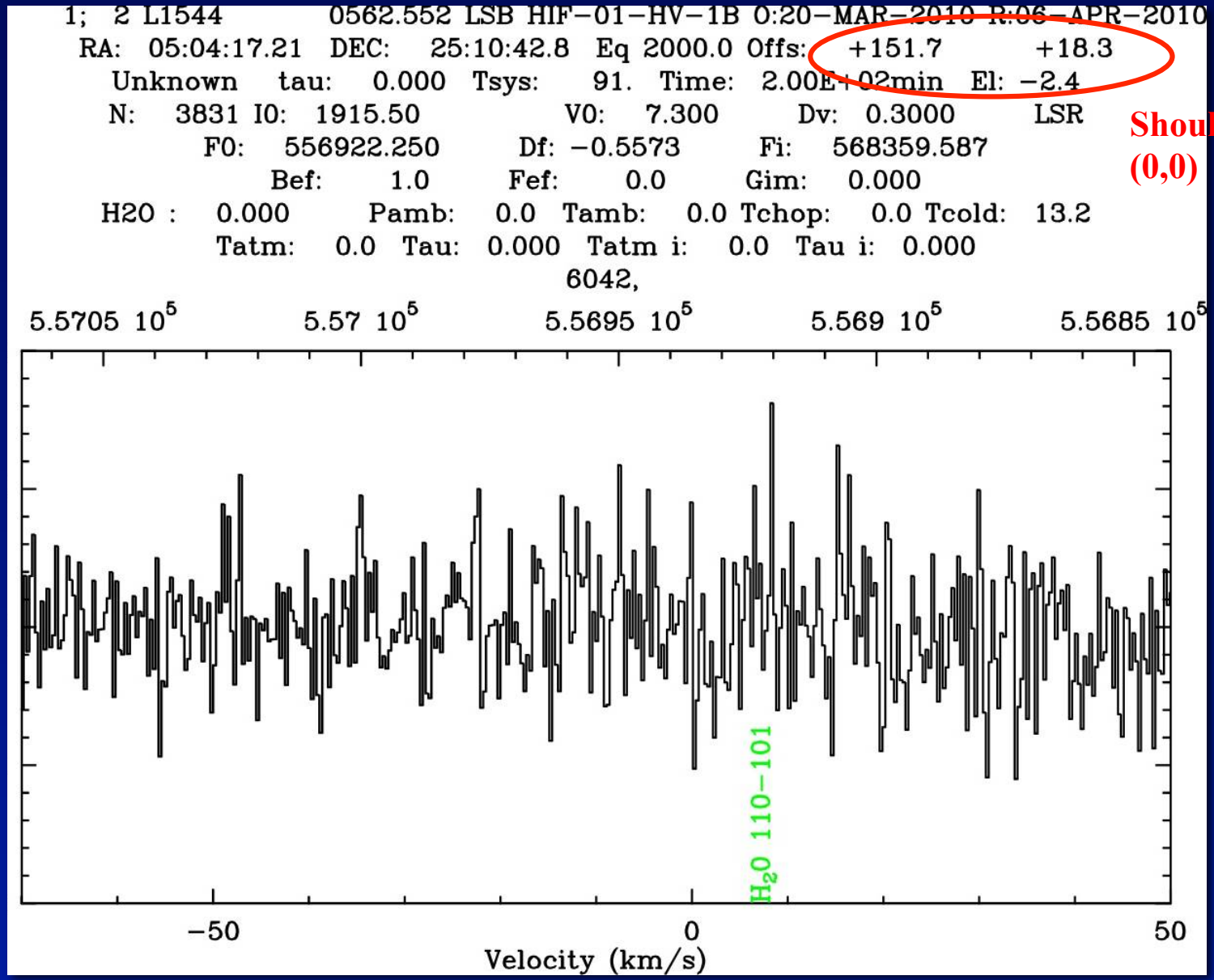
Two sources observed so far

L1544 MODEL (MOLLIE)



Maximum (undepleted-undissociated) H_2O abundance = $5 \cdot 10^{-9}$, from the lowest upper limit found in dark clouds ($<7 \cdot 10^{-9}$; Harju et al. 2009).

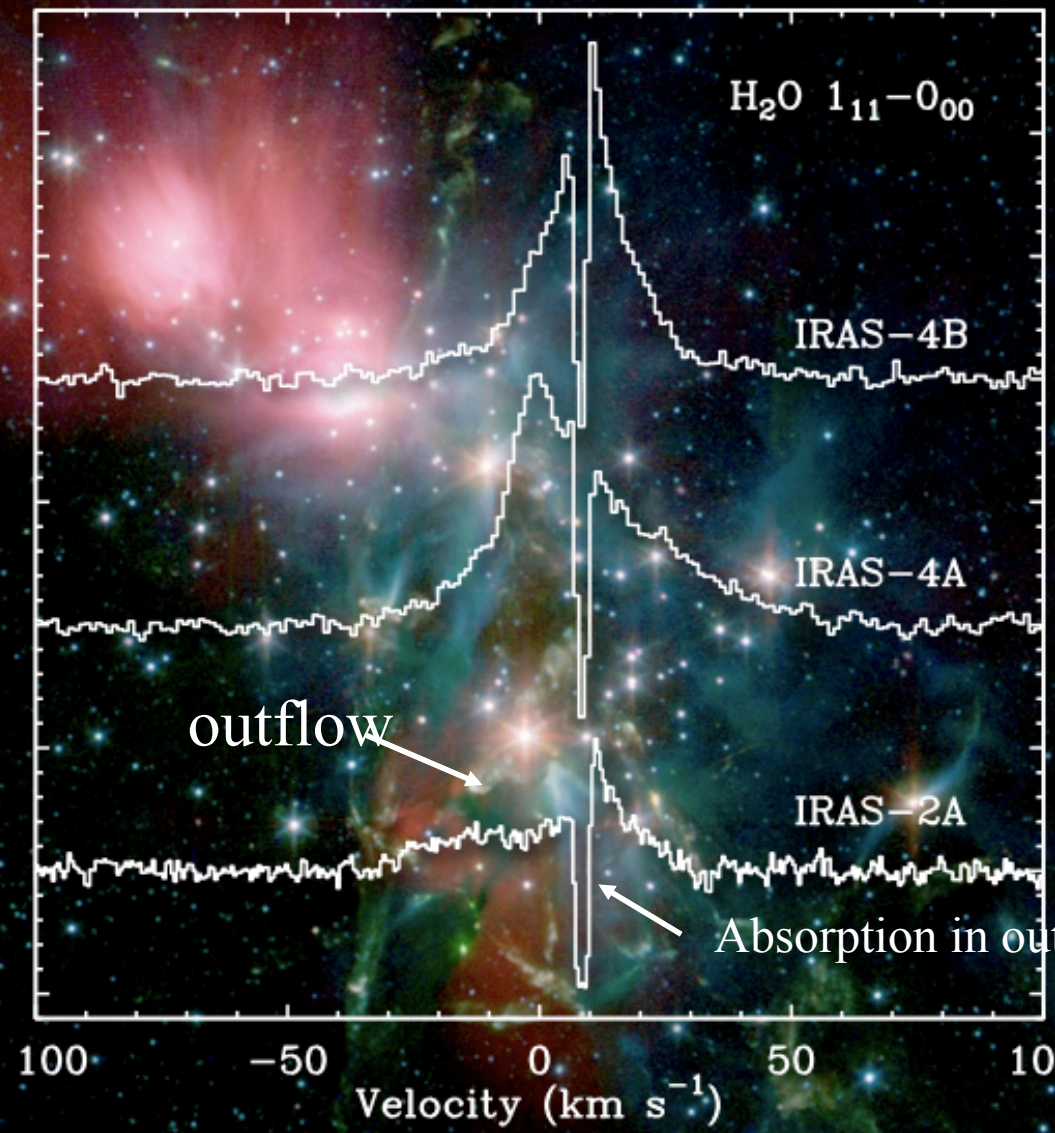
Data convolved with Herschel beam at 557 GHz.



Should be (0,0)

Non detection consistent with $x(H_2O) < 10^{-9}$ at $n(H_2) = 10^5$ cm^{-3}, T = 10 K and Δv=0.5 km/s or $x(H_2O) < 10^{-8}$ at $n(H_2) = 10^4$ cm^{-3}, T = 10 K and Δv=0.5 km/s

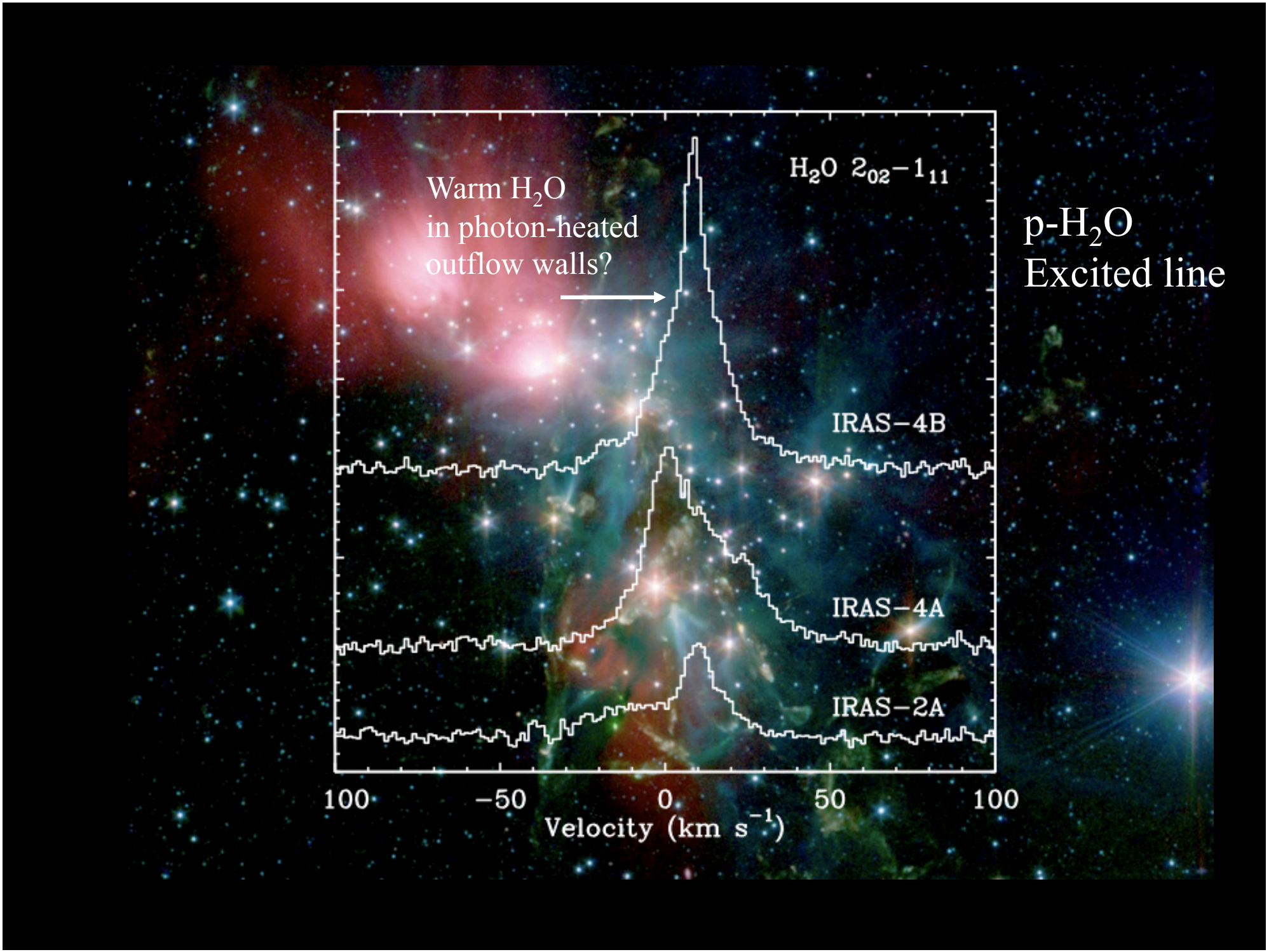
Low-mass YSOs: NGC 1333



p-H_2O ground-state line

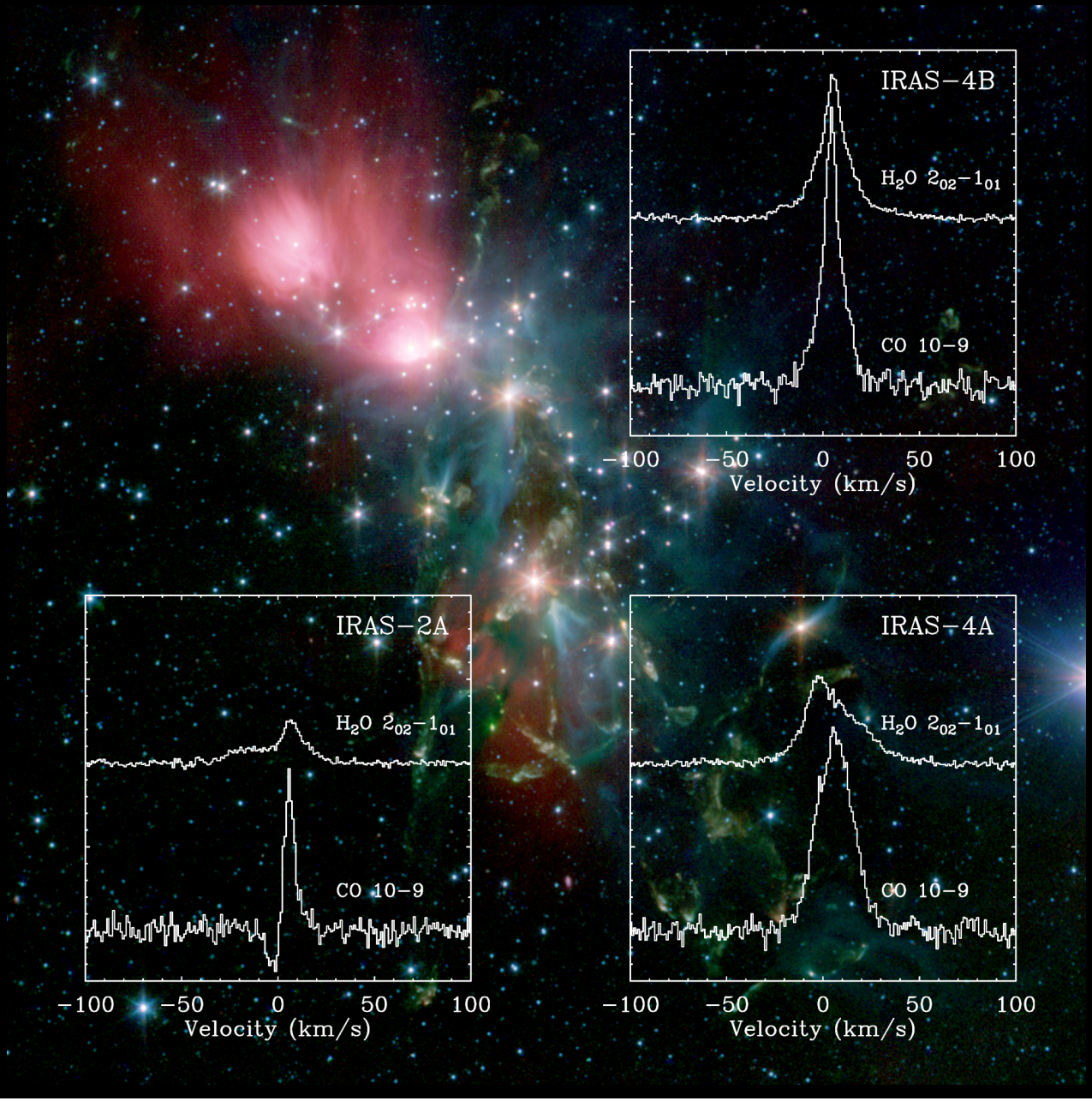
$H_2{}^{18}O$ detected: broad lines

Kristensen, Visser et al. in prep



p-H_2O
Excited line

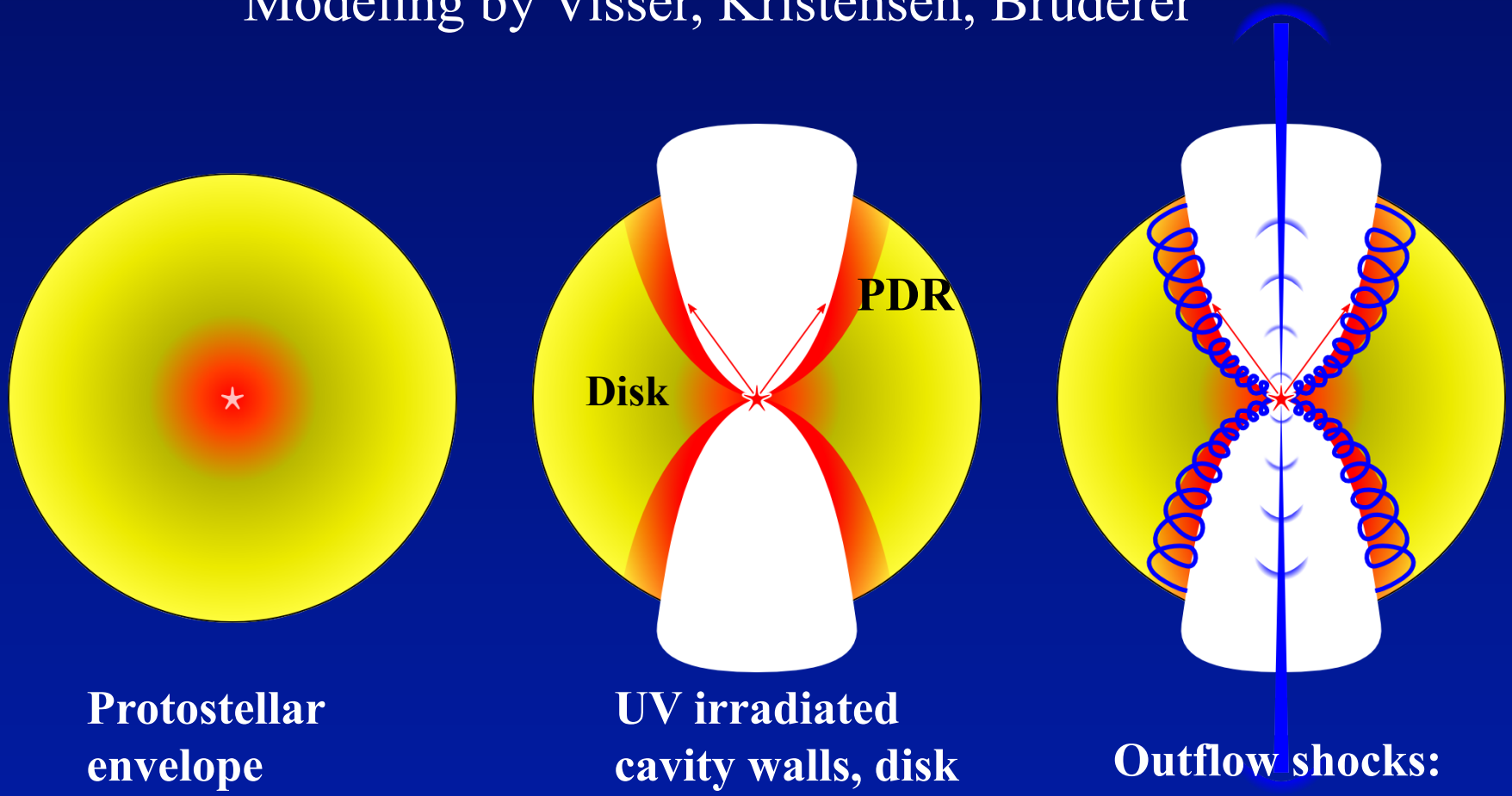
Comparing CO and H_2O



Yildiz et al.,
In prep

Which physical component dominates which lines?

Modeling by Visser, Kristensen, Bruderer

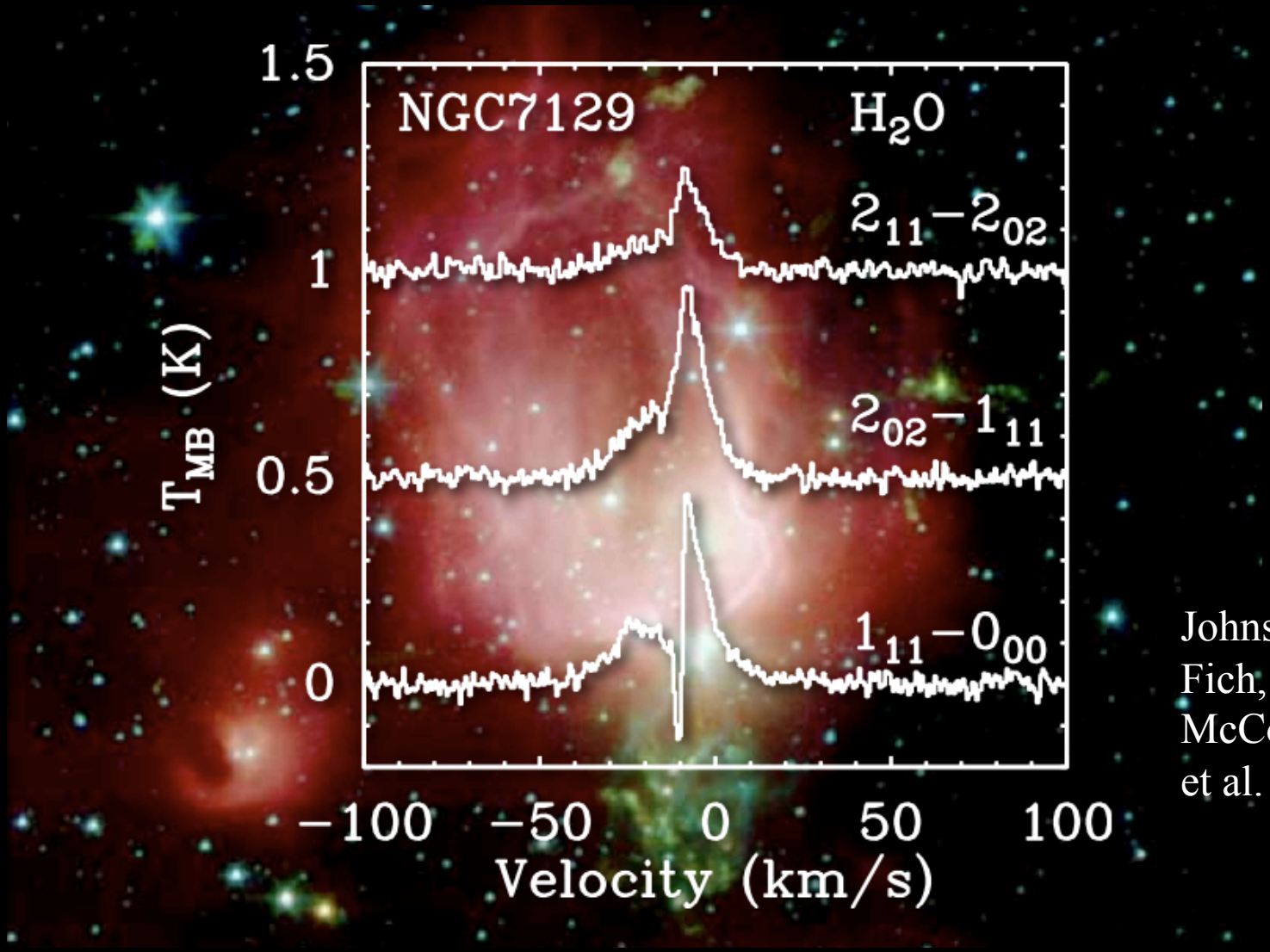


Protostellar envelope with hot core:
Low-J CO

UV irradiated cavity walls, disk surface:
Mid-J CO
Hot water?

Outflow shocks:
High-J CO,
Hot water?
High velocity O I

Intermediate mass YSO program



Johnstone, Fich, McCoey et al.

- Good data, planning O.K.

High-mass star formation

Outline of program

Pre-stellar cores
G11.11−0.12-NH_3-P1
G11.11−0.12-SCUBA-P1
G28.34+0.06-NH_3-P3
G28.34+0.06-SCUBA-P2

mIR-quiet HMPOs
IRAS05358+3543
IRAS16272−4837
NGC6334-I(N)[a]
W43-MM1
DR21(OH)[a]

mIR-bright HMPOs
W3-IRS5
IRAS18089−1732[a]
W33A[a]
IRAS18151−1208
AFGL2591[a]

Hot Molecular Cores
G327−0.6
NGC6334-I[a]
G29.96−0.02[a]
G31.41+0.31
(IRAS20126+4104)

UC HII Regions
G5.89−0.39
G10.47+0.03
G34.26+0.15
W51N-e1[a]
NGC7538-IRS1[a]

- Abundance + distribution of H_2O in envelopes:

pointed HIFI obs of 13 lines in 19 sources

- Water in massive outflows:

557 GHz mini-map

- Kinematics and geometry of warm inner envelopes:

PACS spectro-imaging of CO, O, OH, H_3O^+, high-*J* H_2O

- Chemistry of massive pre-stellar cores:

deep HIFI 557 GHz obs of four infrared-dark cloud cores

- Filling, cooling & chemistry of intra-cluster gas:

5-10 arcmin^2 HIFI + PACS maps in 4 lines of 6 proto-clusters

Bits + pieces of PSP1+2 done

Max-Planck-Institut für Radioastronomie

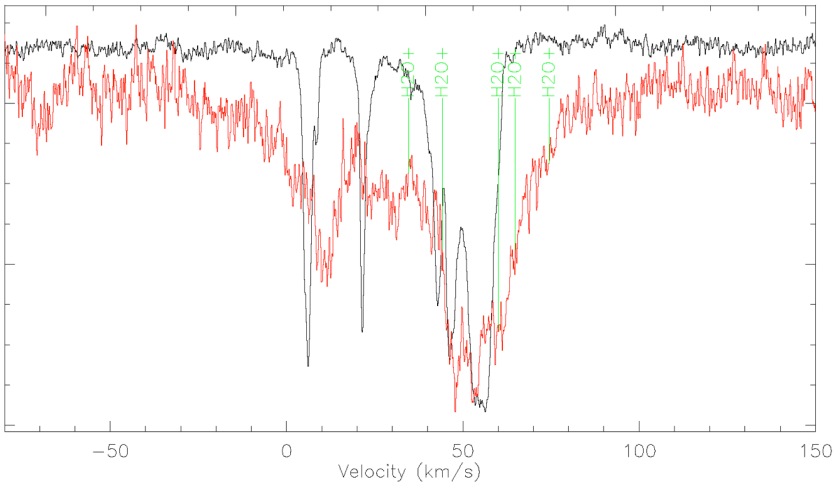
Are the scientific goals reached ?

- In progress, but very promising !!

⇒ **3 papers to be submitted** to the HIFI special issue of A&A.

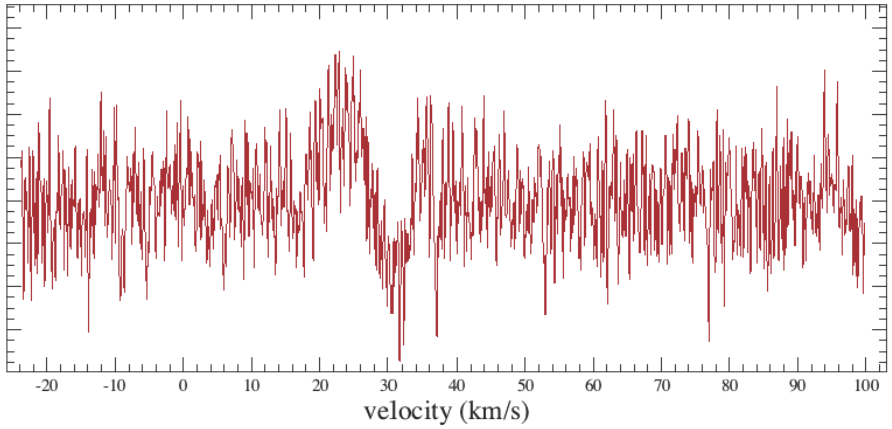
+ **1 paper submitted** to the A&A HSO special issue

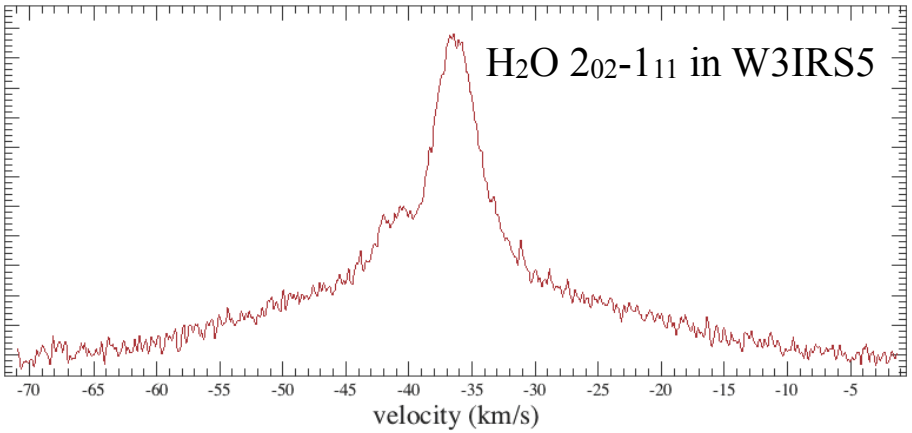
- **Lines are well detected** with a lot of informations coming from the **velocity profile** (thanks to the HRS !!)
- New detections: H2O+



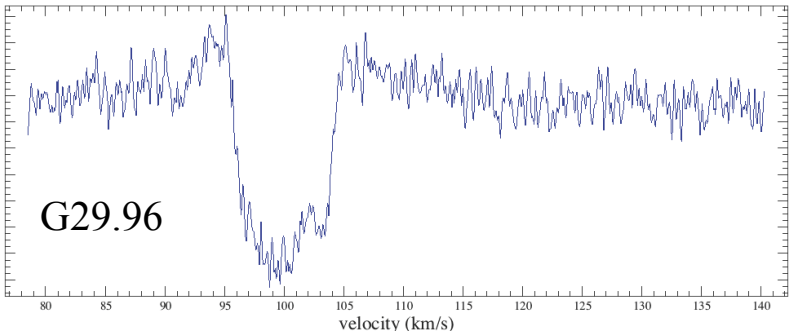
G34.26: H_2O^+ line in red (water in black)

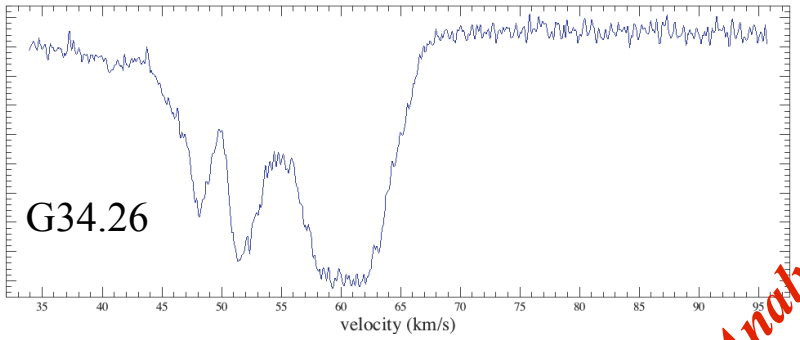
H_2O 1_{10}-1_{01} in prestellar core G11.11 SCUBA-P1

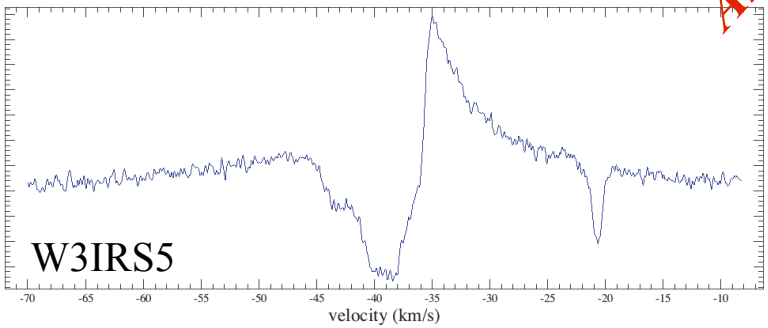


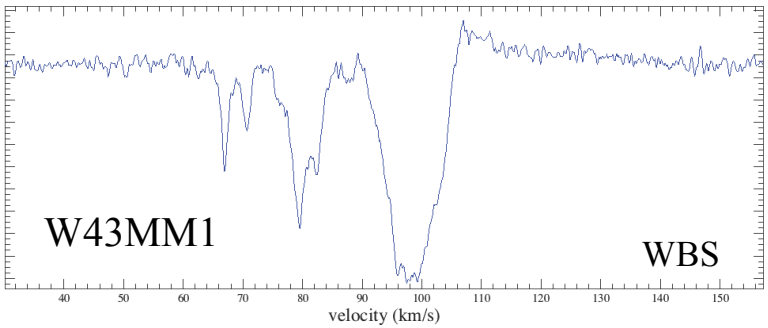


H_2O 1_{11}-0_{00} (HRS spectra with continuum)

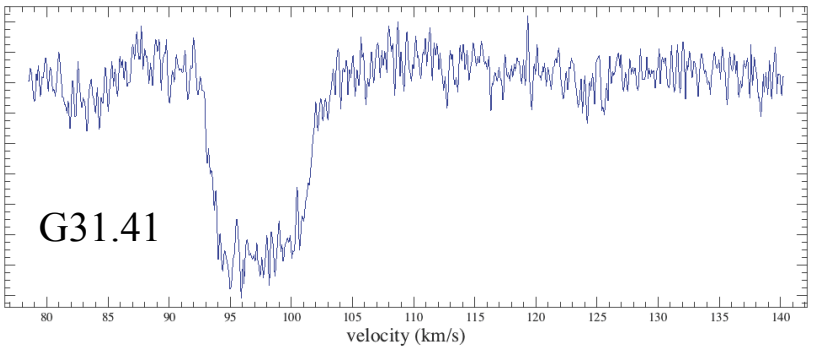


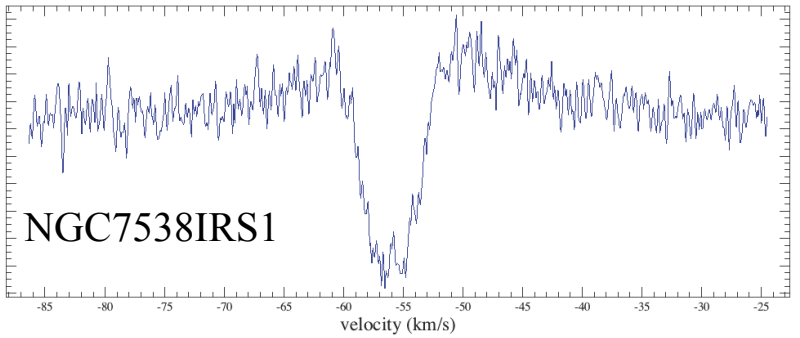


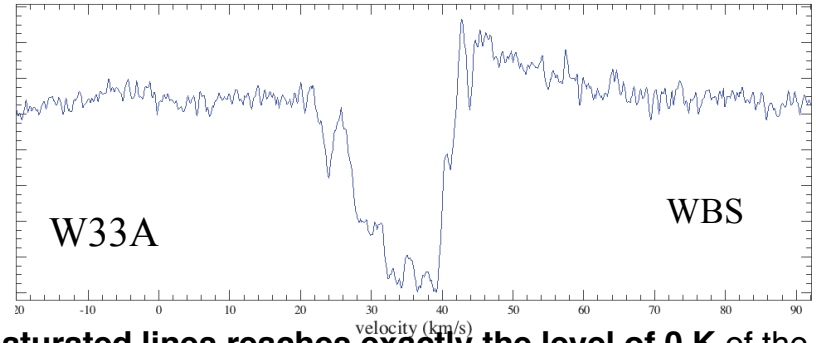




Analysis on-going !!







self-absorbed saturated lines reaches exactly the level of 0 K of the profile ⇒ continuum calibration in HIFI observations is correct

Predicted by models of water ground-state emission lines, in the case where **$X_{H2O} \sim 10^{-8}$, i.e. high abundances.**

This is particularly visible in G31.41+0.31, a HMC, but also detected in other HMC sources, where having this high abundance of water makes perfectly sense.

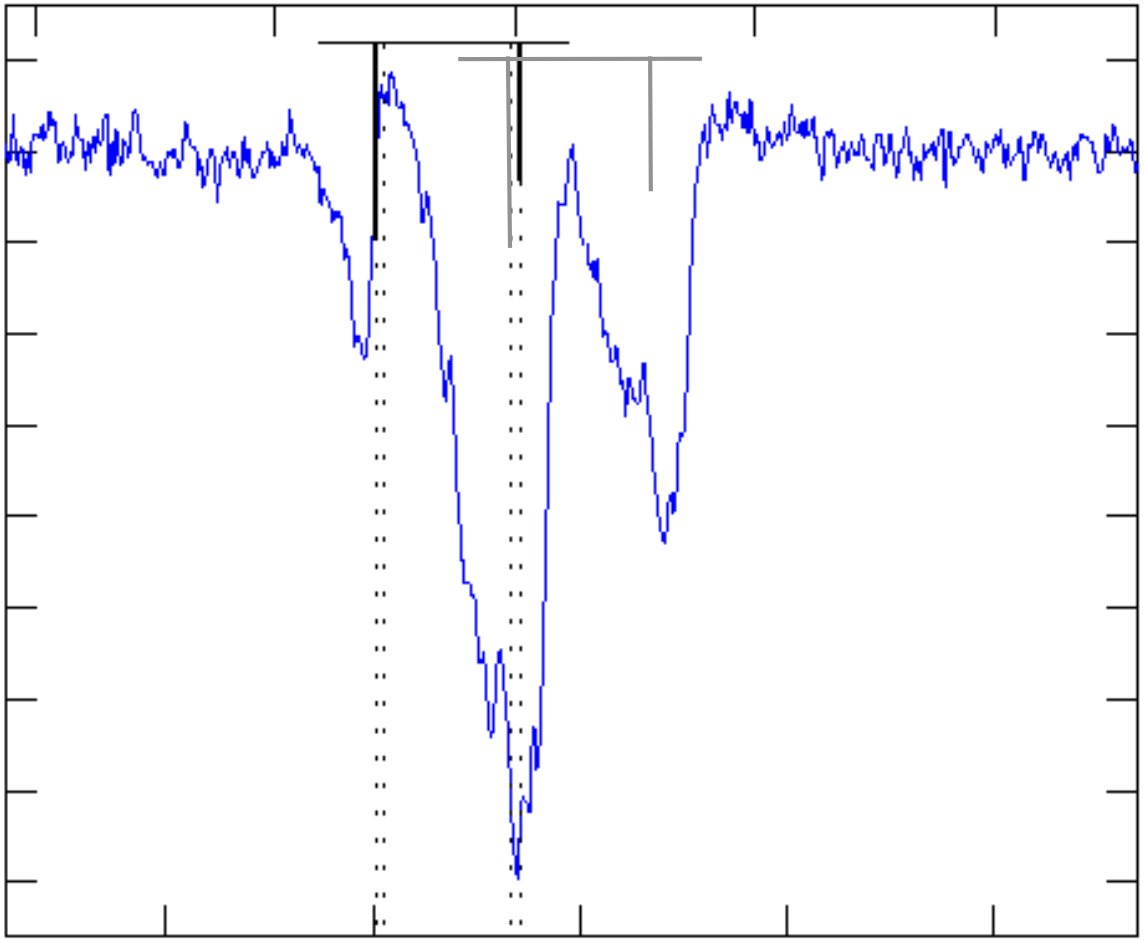
Radiation Diagnostics

Arnold O. Benz
Simon Bruderer
Pascal Stäuber
Susanne Wampfler
Carolin Dedes
Ewine F. van Dishoeck

ETH Zurich

Institute of Astronomy,
Star and Planet Formation Group

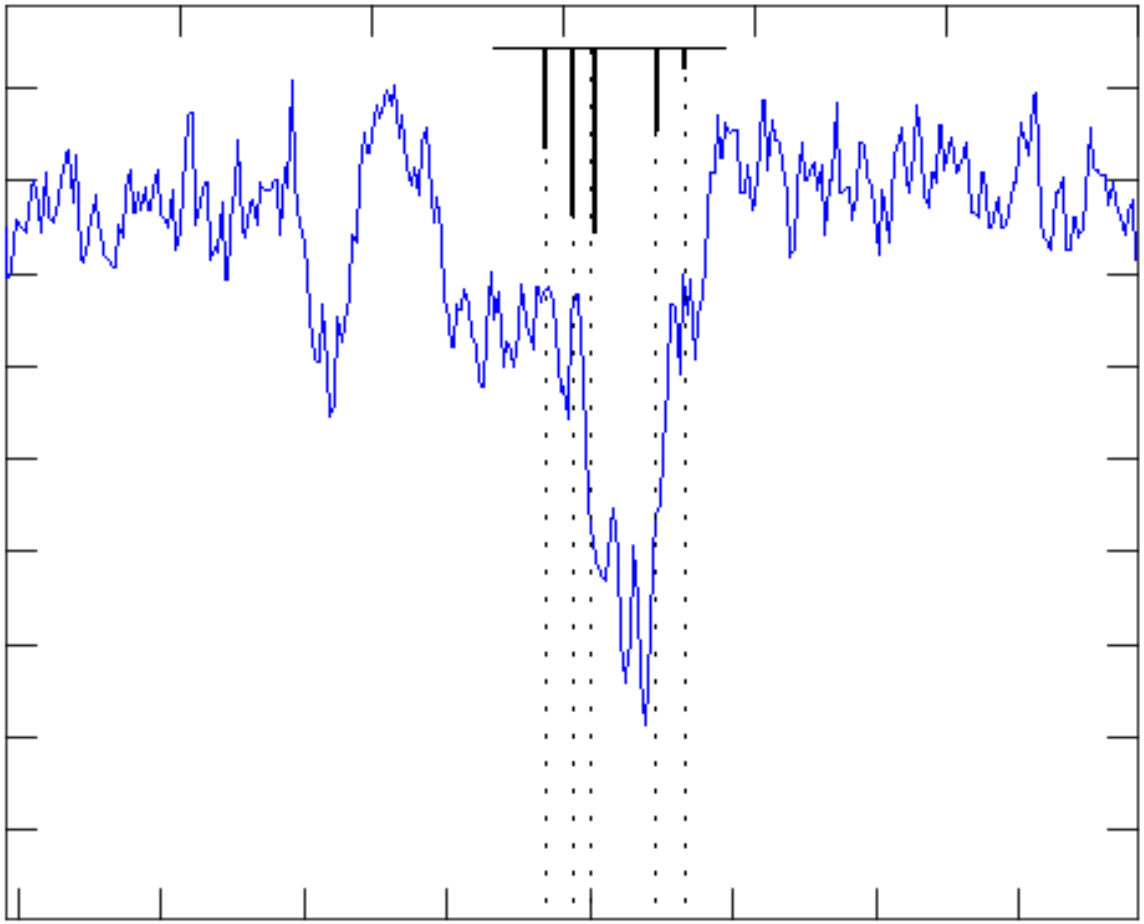
`New‘ molecule: OH^+



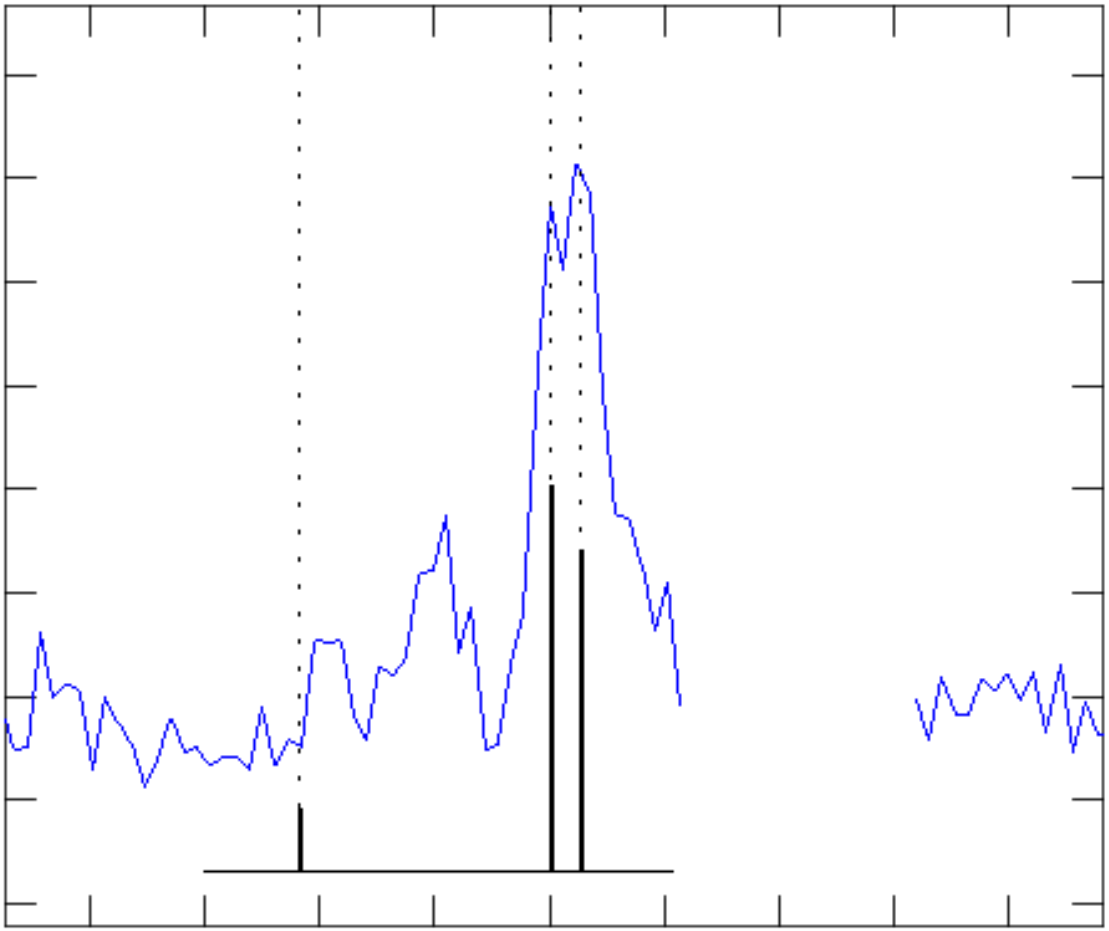
Source
Vel. = 0

OH^+ also detected from ground by APEX (Wyrowski et al. 2010)

New molecule: H_2O^+

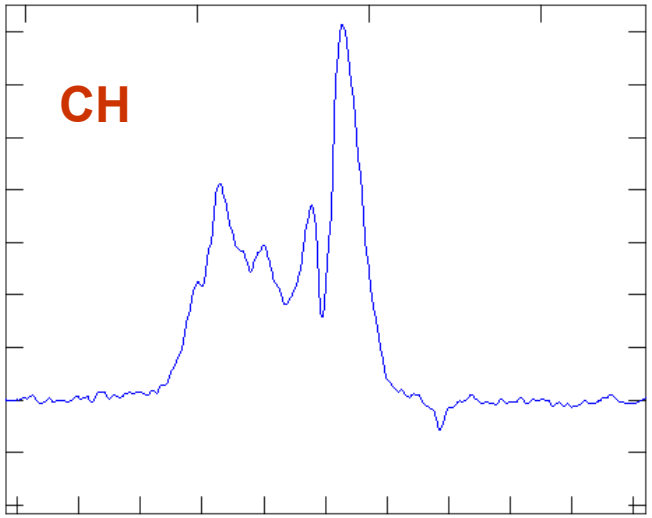


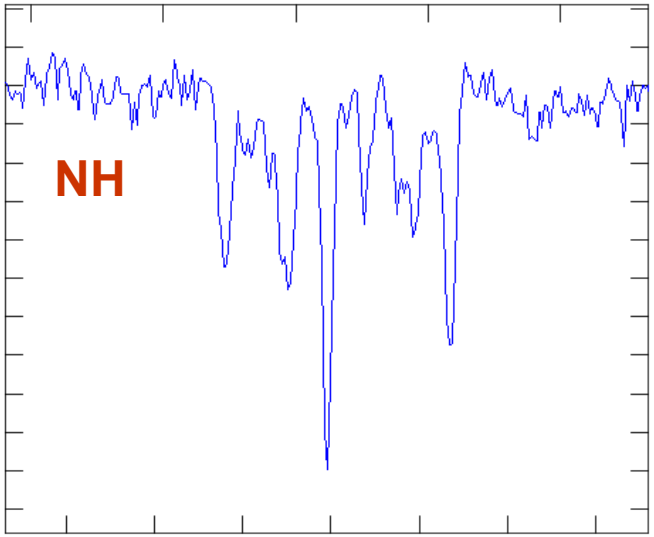
`New molecule‘: SH^+

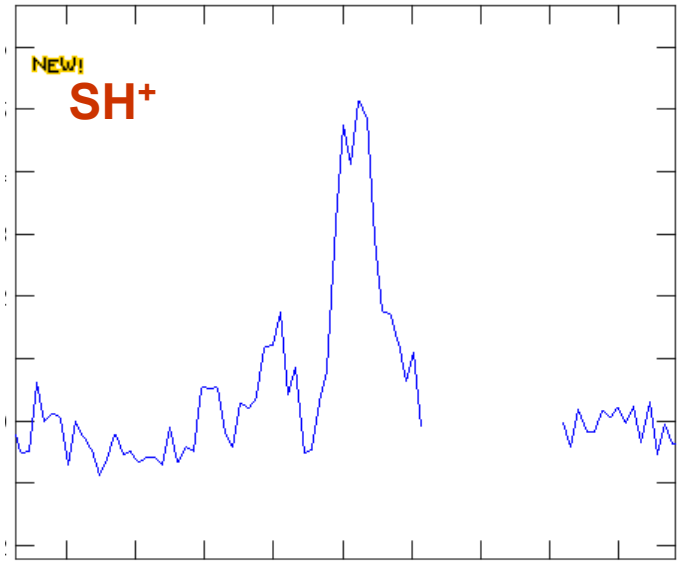


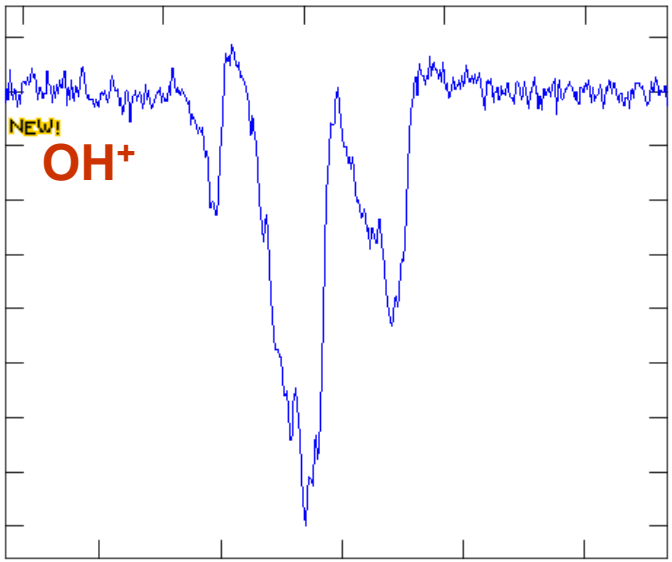
SH^+ also detected from ground by APEX (Menten et al. 2010)

Hydrides in High-mass Star Forming Region

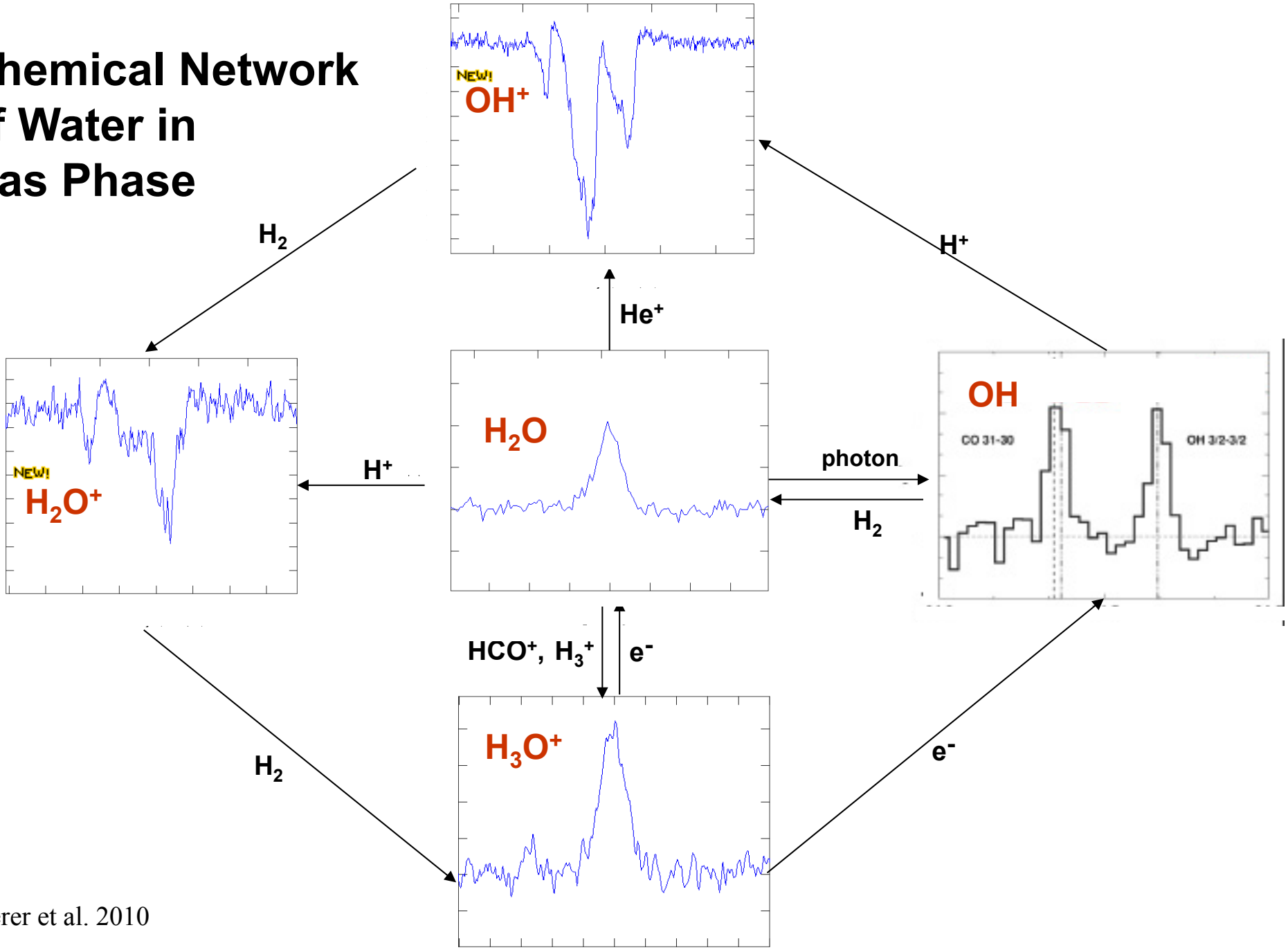




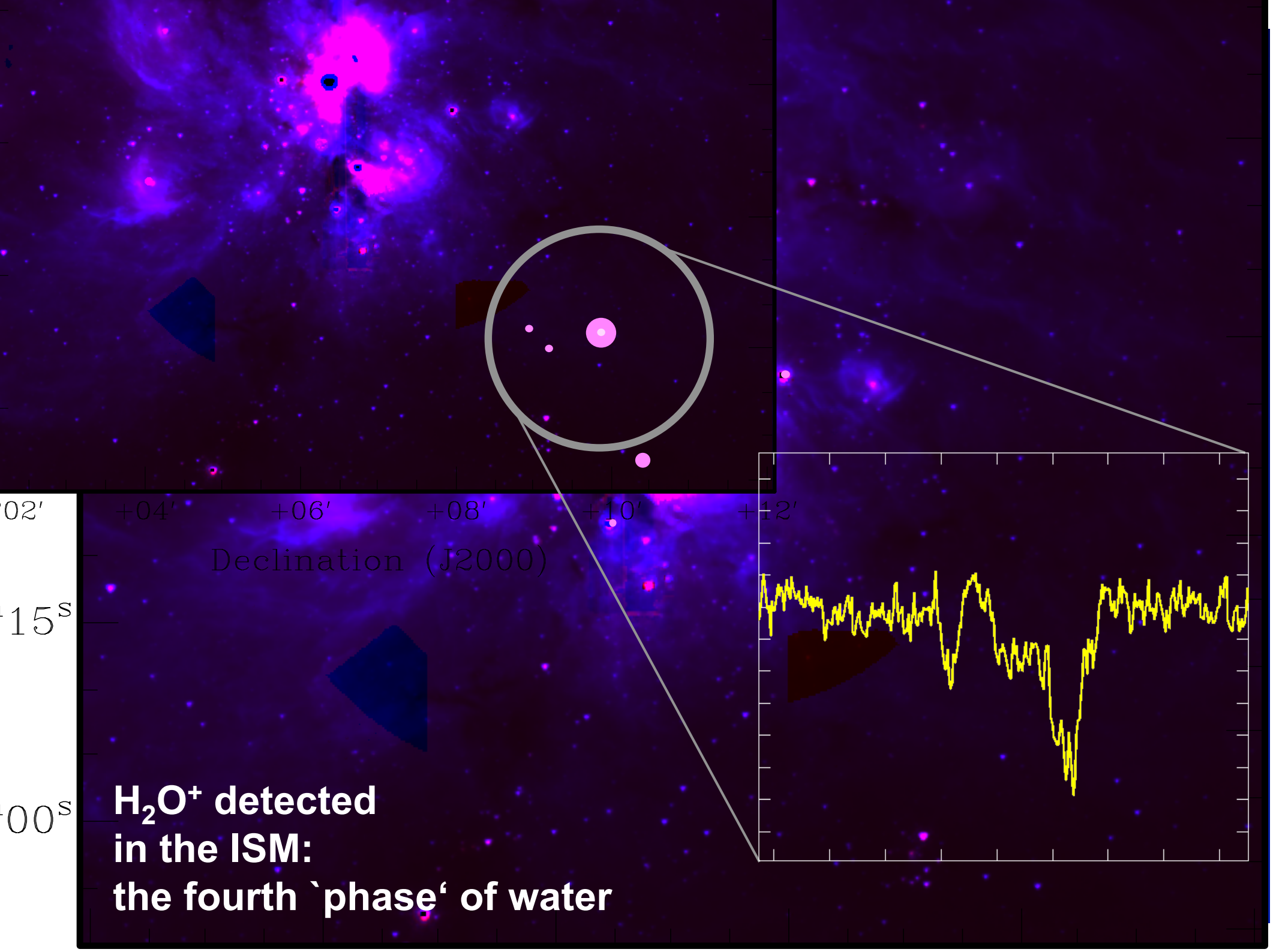


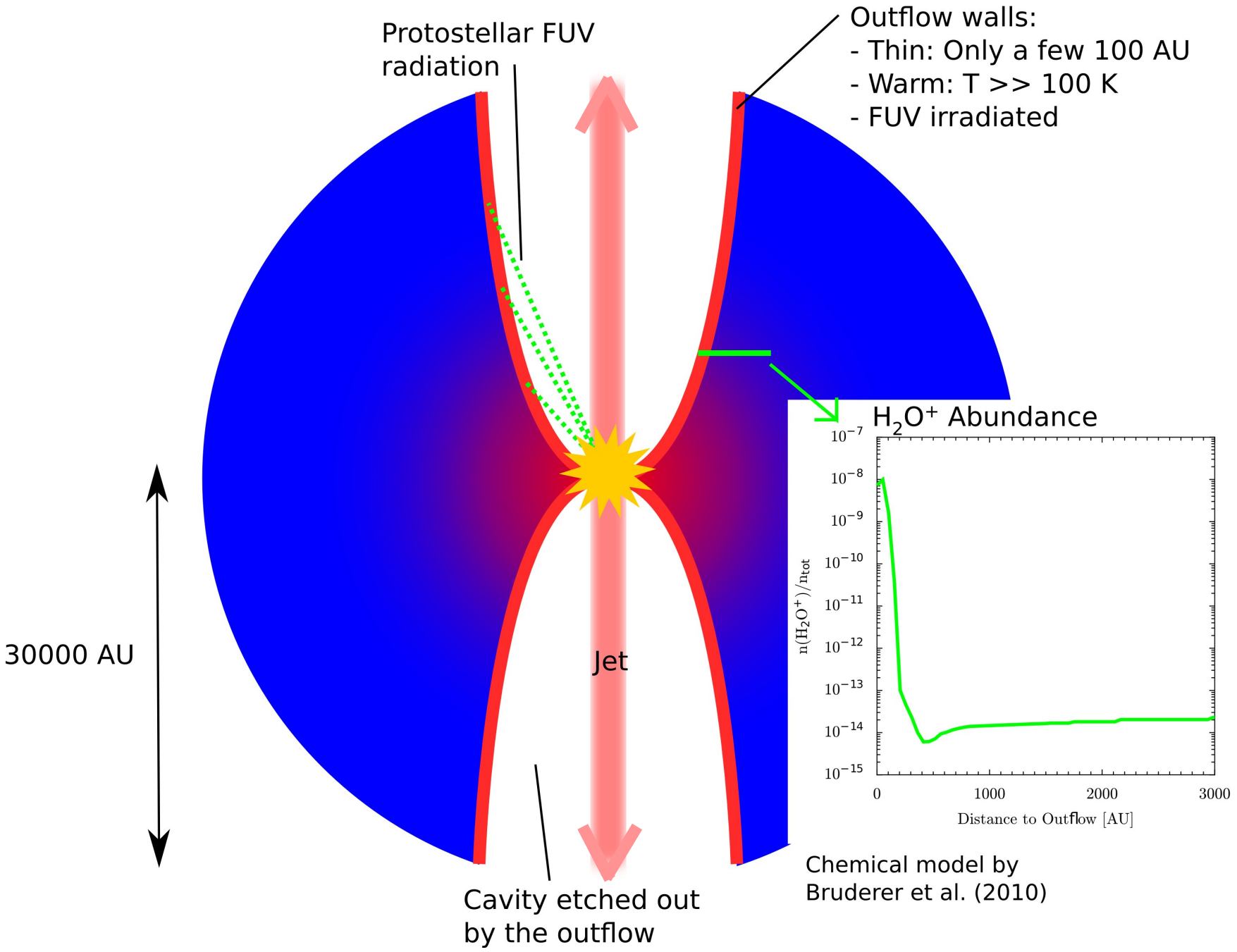


Chemical Network of Water in Gas Phase



Bruderer et al. 2010


+04′
+06′
+08′
+10′
+12′
Declination (J2000)
15ˢ
00ˢ
H2O+ detected
in the ISM:
the fourth `phase‘ of water



H_2O^+, OH^+, CH^+, and SH^+ are the paint on the outflow wall

Radiation Diagnostics Summary

1. Molecules under UV irradiation (and X-rays?) in high-mass objects detected as hoped

2. `New‘ molecules: H_2O^+, OH^+, SH^+

3. Not as predicted: line shape, velocity shift, absorption/emission

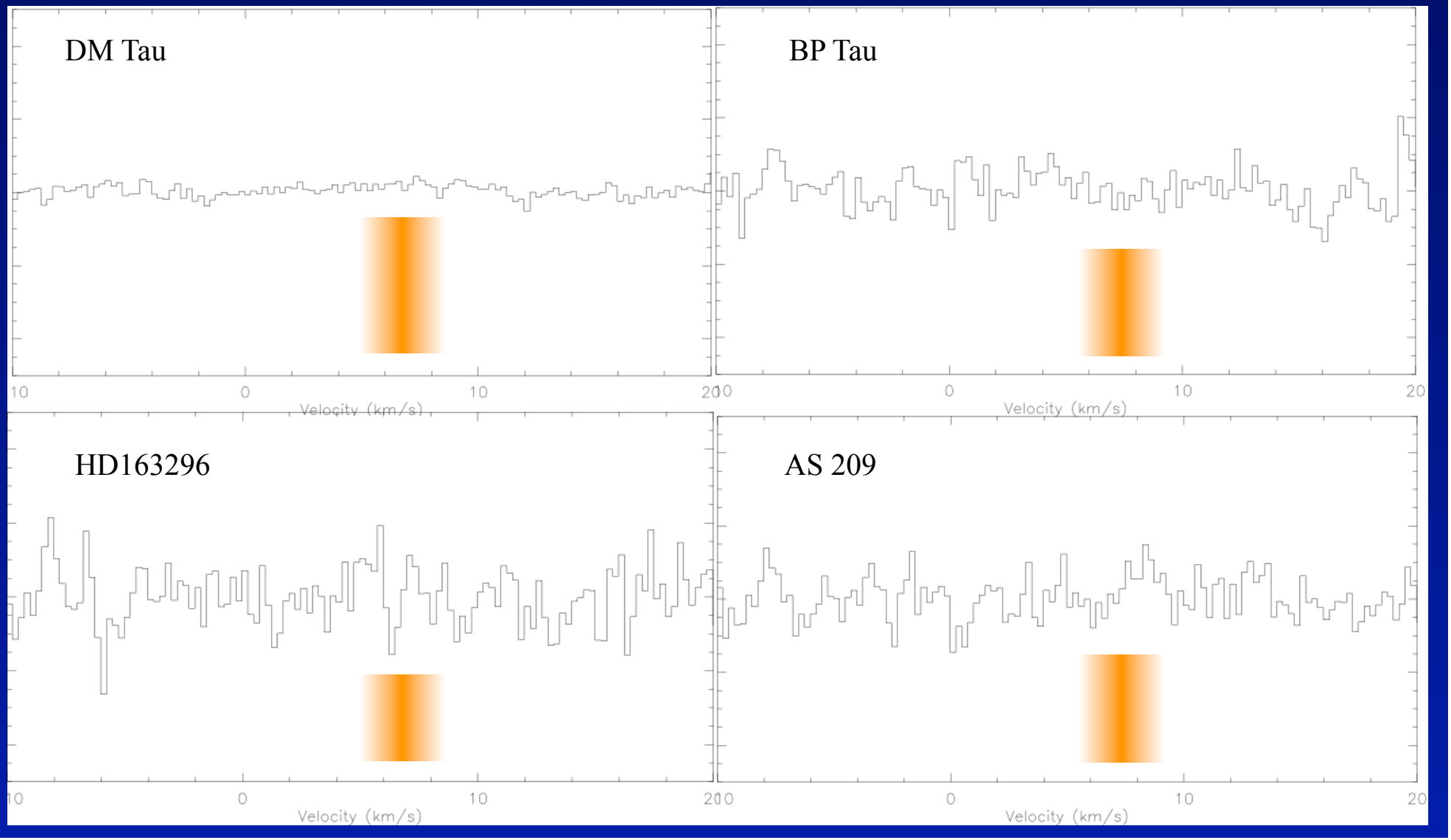
4. Most ionized molecules more intense than predicted

Disks

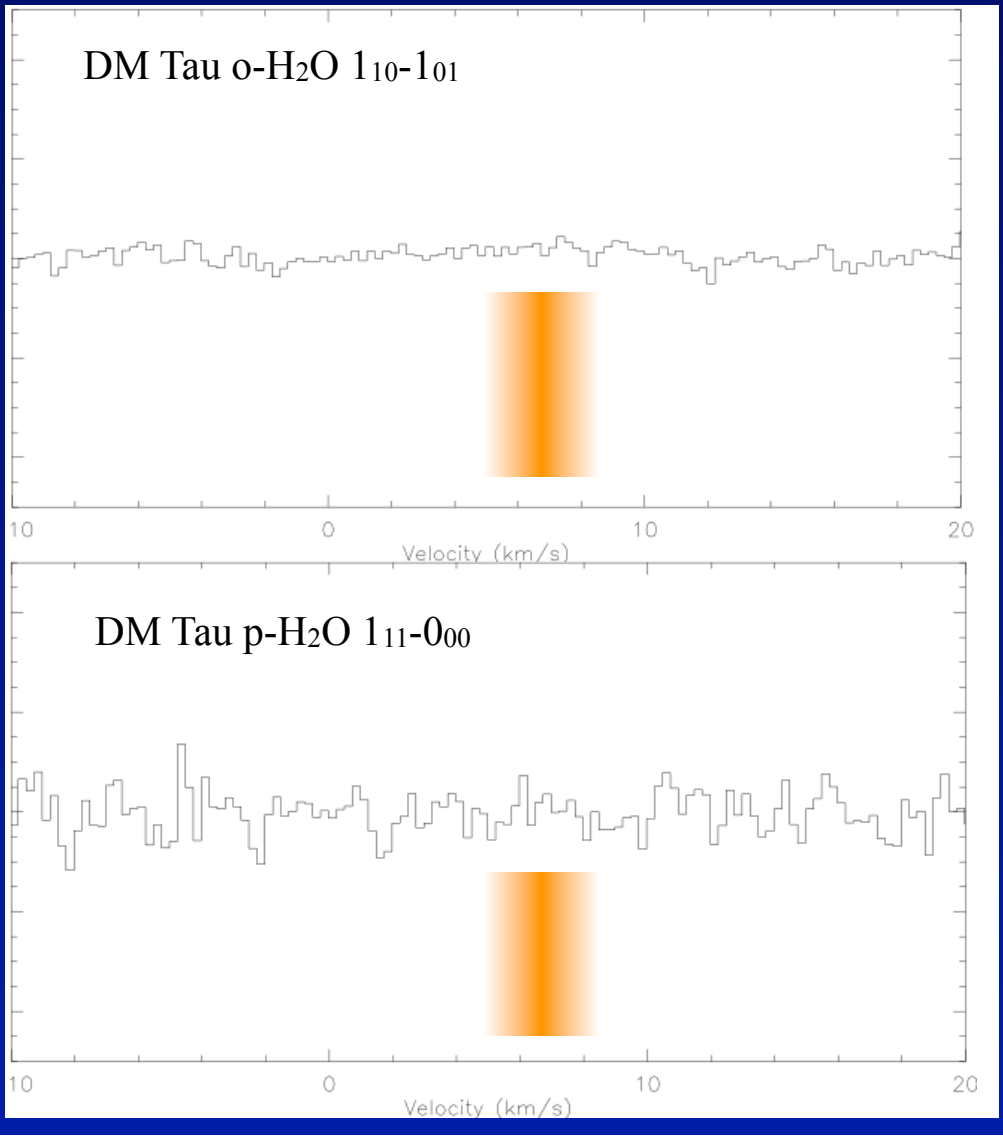
- To detect cold water vapor in protoplanetary disks
- Sample
  - well studied objects with gas-rich disks
  - 4 ‘deep’ targets: DM Tau, LkCa15, TW Hya, MWC480
  - 8 ‘shallow’ targets: BP Tau, AS209, HD163296, IM Lup, GG Tau, MWC 758, T Cha, GM Aur
- o-H_2O 1_{10}-1_{01} to 3σ=4.5 mK (15 mK) in 0.5 km/s
- p-H_2O 1_{11}-0_{00} to 3σ=12 mK (44 mK) in 0.5 km/s

Michiel Hogerheijde, Carsten Dominik, Ted Bergin, Geoff Blake, John Pearson, Gary Melnick, Dave Neufeld, Darek Lis, Olja Panic, Christian Brinch, Ewine van Dishoeck, Lars Kristensen, Umut Yildiz, José Cernicharo

Disks: upper limits



Disks: DM Tau vs models



Models predict line intensities of a few to several tens of mK.

Observations rule out some models.

Comparison to amount of 'warm' CO (e.g., CO 6-5, ~80-100 K) and CI may be essential to see if

– disks lack warm gas
– warm gas in disks is 'dry'
– water vapor at low T is 'dark'

Now that it seems that disks are 'dark' in the ground state lines, consider to focus on a higher excitation water line.

Conclusions

- **WISH program and approach generally validated**
- **Balance HIFI-PACS lines largely O.K. (see also Kristensen talk), but minor tweaks needed as analysis progresses**
  - **E.g., more highly excited H_2O lines**