H_2O Emission in Ultra-Luminous Infrared Galaxies at redshift $\sim$ 2–4

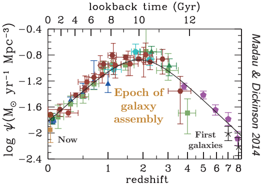
Chentao Yang

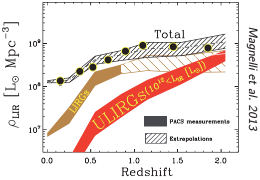
with **A. Omont, A. Beelen, E. González-Alfonso, R. Neri, Y. Gao, P. van der Werf, A. Weiß, R. Gavazzi, N. Falstad, R. S. Bussmann, R. Ivison, M. Spaans**, et al. on behalf of the ***Herschel*-ATLAS team**

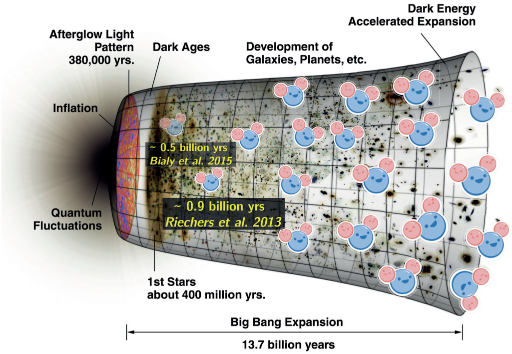
Thanks to IRAM

Water in the Universe @ESTEC, Noordwijk, 15/04/2016

The big picture - understanding the galaxy mass assembly



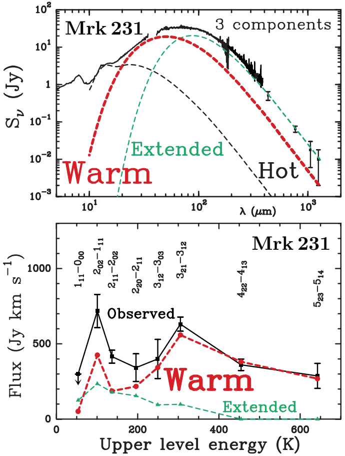




- Studying high-redshift ULIRGs is the key to understand the star formation → galaxy mass assembly.
- After CO, H_2O is one of the most important molecules probing the ISM:
  - H and O are among the most abundant elements. H_2O is almost everywhere in the universe.
  - H_2O is a different diagnostic from CO, sometimes comparable or even brighter than CO.

Demonstrating the diagnostic power of H_2O

e.g., in Mrk 231: *González-Alfonso+2010*; APM08279*: van der Werf +2011; Lis+2011; Bradford+2011;* HLSJ091828: *Combes+2012;* HFLS3: *Riechers+2013; ...*

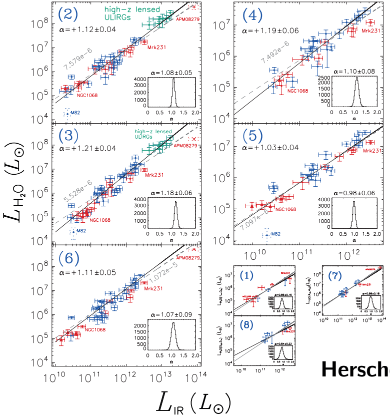


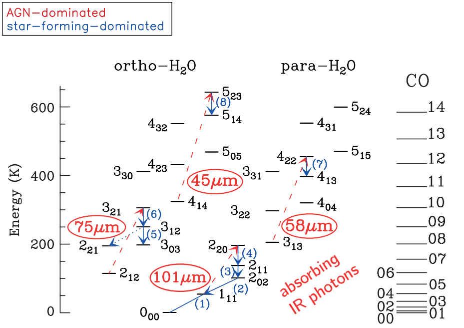
adapted from *González-Alfonso et al. 2010*

H_2O: **a powerful diagnostic tool !**

- IR-pumping dominated ($J \geq 2$)
- A very different tracer from CO
- High-J and low-J H_2O lines are comparable (unlike our Galaxy, dominated by low-J H_2O).
- Intensity ratio of H_2O/CO ~0.3-1 (unlike in Orion Bar ~0.02).
- Generally, H_2O lines diagnostic tells:
  - Column density of H_2O
  - Properties of FIR radiation field: e.g., $T_{\rm warm}$, opacity, ...

A first systematic study of submm H_2O in local galaxies





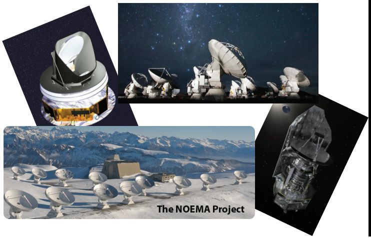
Herschel SPIRE/FTS archive survery: *Yang et al., 2013*

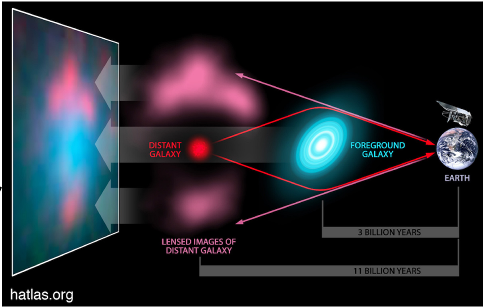
(see also *Master Thesis of Chentao Yang, 2013*)

- First systematic study of submm rotational H_2O emission lines in local infrared galaxies (45 out of 176)
- L_{H_2O} is roughly proportion to L_{IR}: Confirm the importance of IR pumping for the submm H_2O excitation

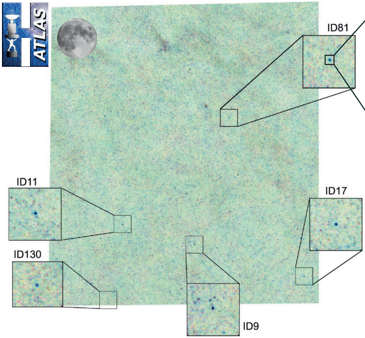
How to observe the submm rotational H_2O lines?

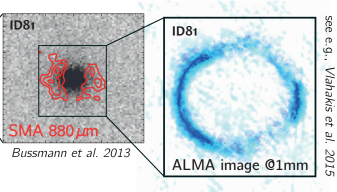
- **In our Galaxy and in nearby galaxies:** very hard to observe from ground
  - Space telescopes: e.g., *Ordin, SWAS , ISO, Herschel*
- **In high-redshift galaxies***:* shifted into atmospheric windows, but very weak
  - Through **gravitational lensing**: picking sources from lensing surveys: e.g., *H*erschel-ATLAS, *H*erMES, SPT and *Planck* all-sky surveys.





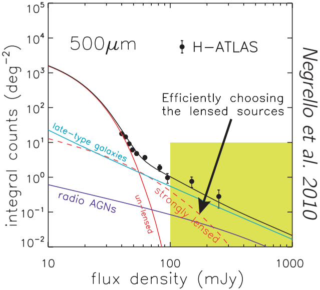
Finding the strongly lensed high-redshift ULIRGs





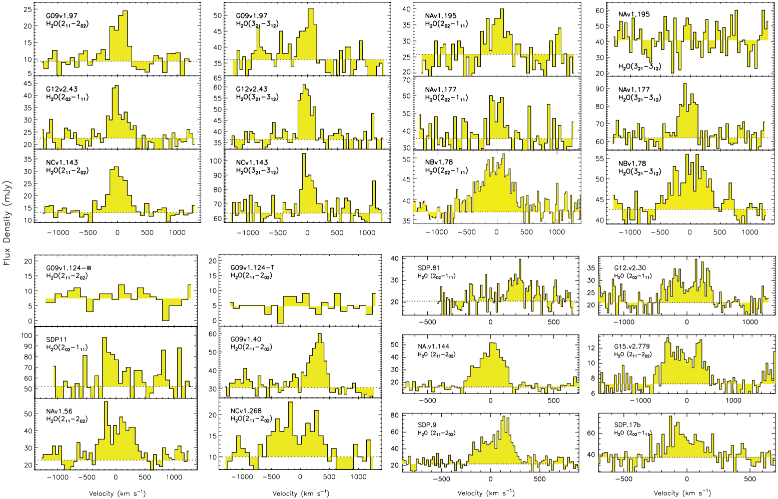
Herschel-ATLAS (*Eales et al. 2010*):

- Widest area survey with *Herschel* (570 deg^2);
- Covering 5 bands from 100 μm to 500 μm;
- **Selecting** strongly lensed candidates by $S_{500\mu m}$>100 mJy;
- Determining the **redshifts** by follow-up CO observations;
- Follow-up imaging observations for bulding **lensing model**;
  (Sample with ~30 sources, Bussmann et al. 2013)



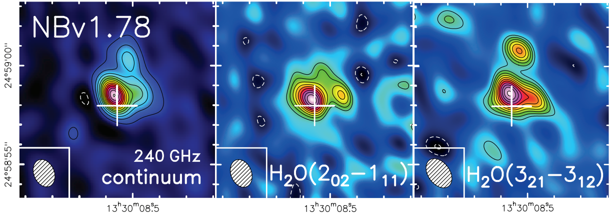
H_2O detections in the *Herschel* high-z lensed ULIRGs

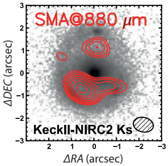
21/23 high-z detections in 17 galaxies: *Omont, et al. 2011, 2013; Yang et al. 2016*



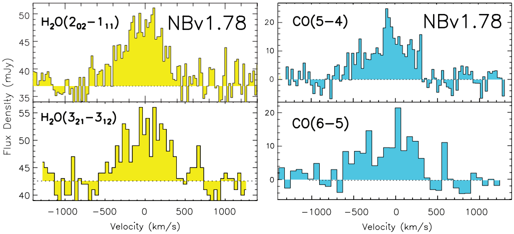
H$_2$O lines of high-redshift lensed ULIRGs (an example)

Omont et al., 2011, 2013; Yang et al., 2016 (A&A submitted)





Bussmann et al. 2013 (BU13)

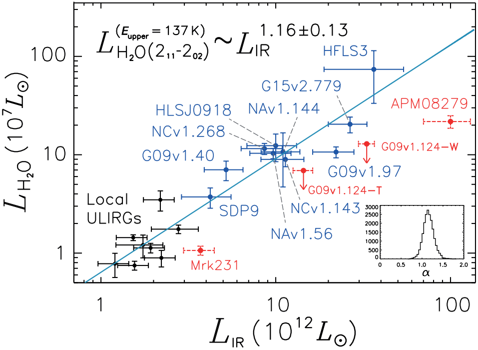


21 good H_2O emission line detections in 16 high-z ULIRGs

- **Largest** study of high-z H_2O;
- z~2-4, cosmic star formation peak;
- $\mu_{lens@880\mu m}$= 2–15 (magnification, from *BU13*);
- L_{IR} = 0.4–2×10^{13} $L_\odot$;
- Σ_{SFR} =100–2000 $M_\odot$ yr^{-1} kpc^{-2};
- **Efficient to detect H_2O** in high-z ULIRGs.

Tight correlations between L_{H_2O} and L_{IR} from local to high-redshift ULIRGs/HyLIRGs

Omont et al. 2013; Yang et al., 2016



$$L^{(E_{upper}=101\,K)}_{H_2O(2_{02}-1_{11})} \sim L_{IR}^{1.06\pm0.19}$$

$$L^{(E_{upper}=305\,K)}_{H_2O(3_{21}-3_{12})} \sim L_{IR}^{1.06\pm0.22}$$

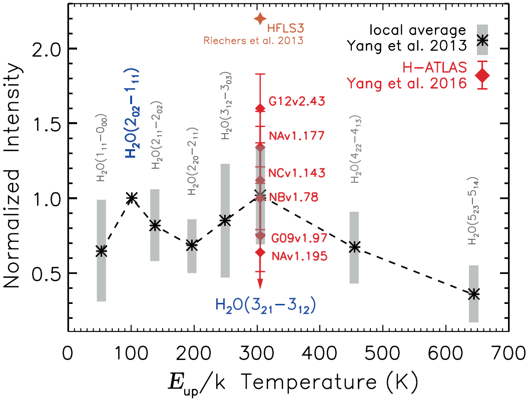
- L_{IR} and L_{H_2O} are roughly propotional
  - Can be explained by the infrared pumping model (González-Alfonso et al. 2014)
- Good tracer of the IR radiation field
  - No AGN signature (mid-IR and radio)
    --> Tracing the IR radiation fields connected to star formation

H_2O Spectral Line Energy Distribution (SLED)

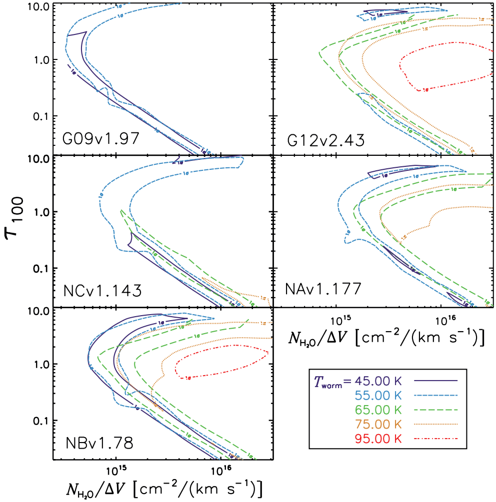
Exploring the H_2O excitation in *Herschel* high-redshift ULIRGs, *Yang et al., 2016*

H_2O SLED normalized by 2_{02}-1_{11} intensity:

- Large variation in the relative strength of higher-excitation line $H_2O(3_{21}$-$3_{12})$.
- Indicating various properties of infrared radiation fields.
- Higher excitation level ($J \geq 4$) H_2O lines are needed in excitation modelling.



Modelling the H_2O gas excitation

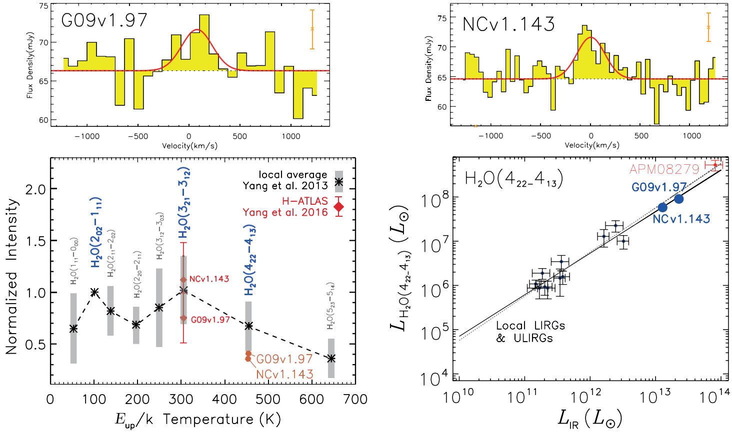


In 5 sources, we have both $J=2$ and $J=3$ H_2O detections:

- IR pumping model from *González-Alfonso et al. 2010, 2014.*
- The H_2O column density is similar to local infrared galaxies.
- H_2O excitation is powered by warm dust component ($T_{warm} \sim$ 45–75 K).
- Strong degeneracies: ***J*** $\geq$ **4 H_2O lines are needed** for better constraints (ongoing project).

On-going observations of $J=4$ H_2O lines using NOEMA

L_{IR}-L_{H_2O} correlation and further constraining of the IR pumping model

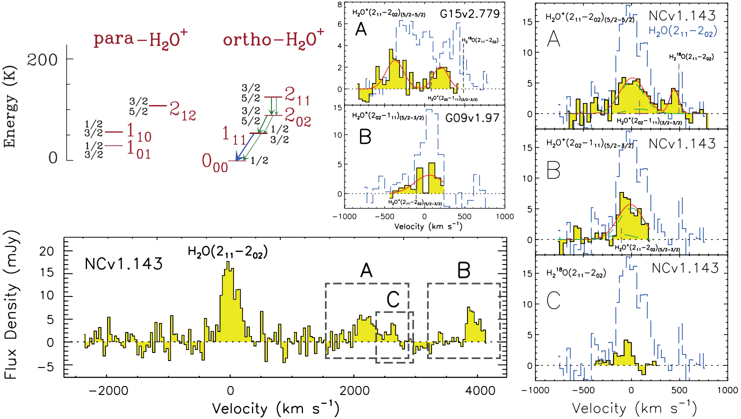


Preliminary results, Yang et al. in prep.

- $J=4$ H_2O is important for constraining the H_2O excitation modelling.

H_2O^+ emission in the high-redshift ULIRGs

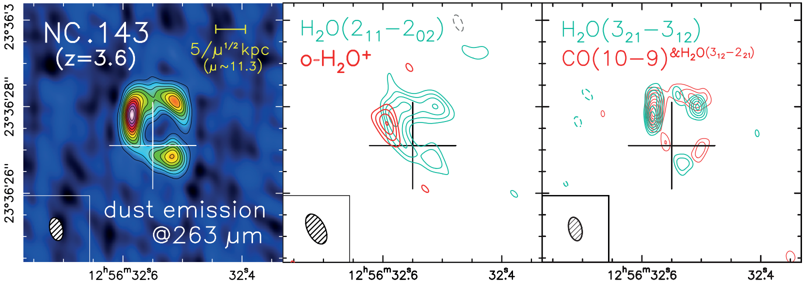
Shedding light on the chemistry of H_2O/H_2O^+ (*Yang et al., 2016*)

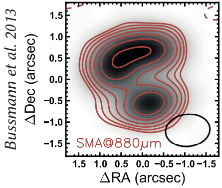


- $H_2O^+/H_2O \sim 0.3$: cosmic rays from star formation may drive the H_2O^+ formation (*Meijerink et al. 2011*).
- H_2O formation is likely to be dominated by the ion-neutral route and/or an undepleted chemistry.

High angular resolution images of the H_2O emission

NOEMA, A-config. *Yang et al, in prep.* (preliminary images we got **yesterday**)





- Comparing the spatial distribution of dust emission, H_2O, H_2O^+ and CO(10-9) emission in sub-kpc scale (+lensing model).
  - Comparing the spatial distributions of different gas tracers.
  - Testing the IR pumping model, and better constrain the physical parameters.
- Building lensing model for each line, "differential lensing free".

Summary

First systematic study of submm H_2O emissions in high-redshift ULIRGs, and the largest sample up to date –

- H_2O is an efficient and important diagnostic tool for the infrared sources in the warm, dense regions linked to intense star formation activities in our high-z ULIRGs. They are strong and comparable with high-J CO lines.
- $L_{H_2O} \sim L_{IR}^{1.1-1.2}$, correlating strongly with star formation.
- IR pumping plays an important role in the submm H_2O excitation and dominates the $J \geq 2$ H_2O excitation.
- $J \geq 4$ H_2O lines are needed for better constraining the IR pumping model.
- H_2O^+/H_2O intensity ratio suggests high ionisation by cosmic rays coming from intense star forming activities.
- High angular resolution images allow us to correctly recover the intrinsic quantities and compare spatial distributions of different gas tracers.

Thanks for your attention and see you in post-doc job market!

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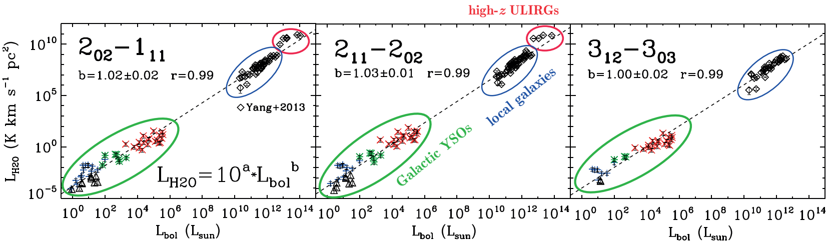
15/04/2016

The linearly correlation down to Galactic YSOs

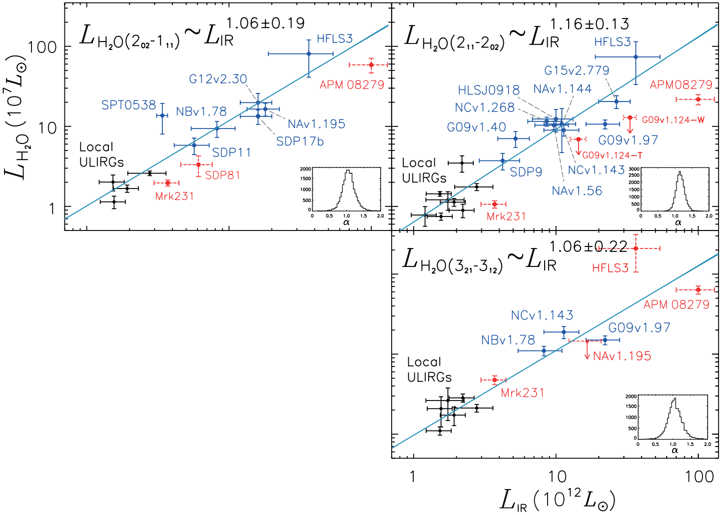


A linear correlation from Galactic YSOs to local galaxies.

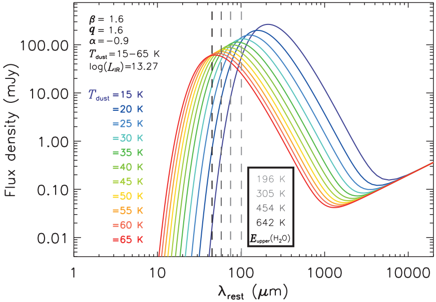
San José-García et al. 2015

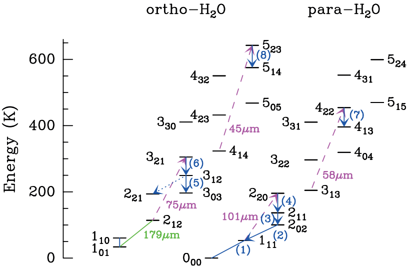
But…still, a lot of physical processes are going on there.

Correlation between the luminosities of H_2O and infrared



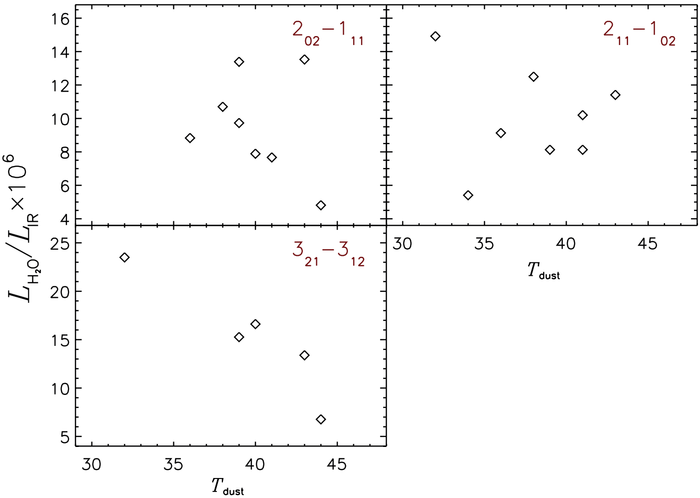
L_{H_2O}/L_{IR} & dust temperature





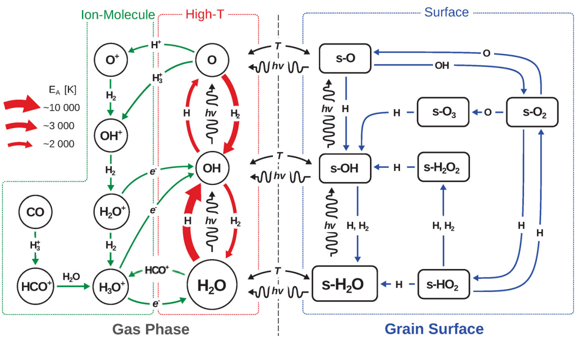
- Line 8 (642K) has strong dependence on T_d, increase with T_d; Line 1-4 have opposite trends.
- Low-lying: $L_{\rm IR}/L_{\rm H_2O}$ decrease with T_d, high-lying: $L_{\rm IR}/L_{\rm H_2O}$ increase with T_d

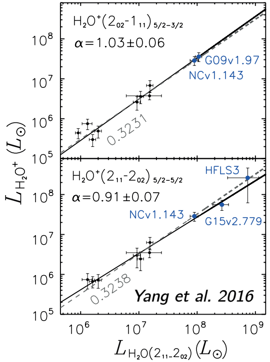
The variation of the L_{H_2O}-L_{IR} correlation with T_{dust}



Where do the H_2O^+ and H_2O come from?

van Dishoeck et al. 2013





- Correlation between H_2O and H_2O^+ from local to high-redshift ULIRGs.
- H_2O formation is likely to be dominated by the ion-neutral route and/or an undepleted chemistry.