

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

Chentao Yang

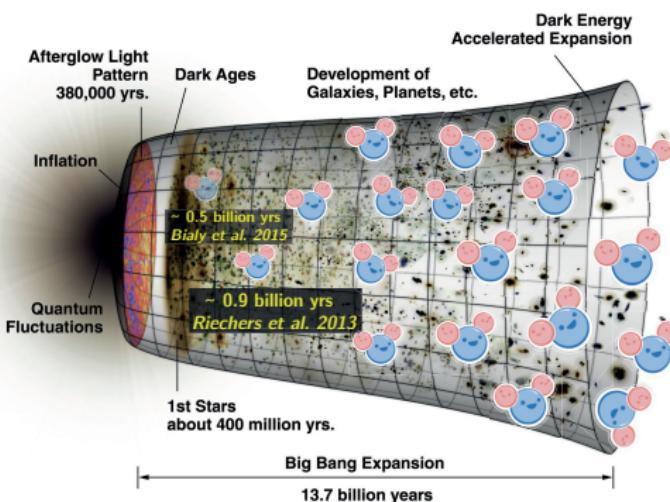
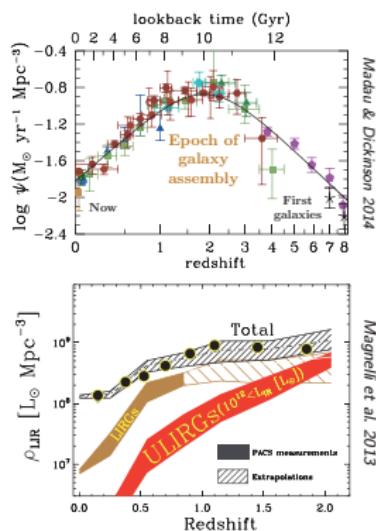
with A. Omont, A. Beelen, E. González-Alfonso, R. Neri, Y. Gao, P. van der Werf, A. Weiβ, R. Gavazzi, N. Falstad, R. S. Bussmann, R. Ivison, M. Spaans, et al. on behalf of the ***Herschel-ATLAS*** team

Thanks to IRAM



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

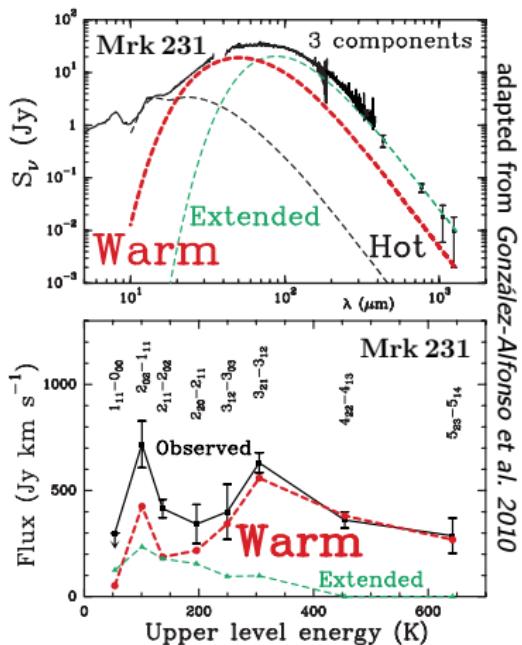
The big picture - understanding the galaxy mass assembly



- Studying high-redshift **ULIRGs** is the key to understand the star formation → galaxy mass assembly.
- After CO, **H₂O** is one of the most important molecules probing the ISM:
 - H and O are among the most abundant elements. H₂O is almost everywhere in the universe.
 - **H₂O** is a different diagnostic from CO, sometimes comparable or even brighter than CO.

Demonstrating the diagnostic power of H_2O

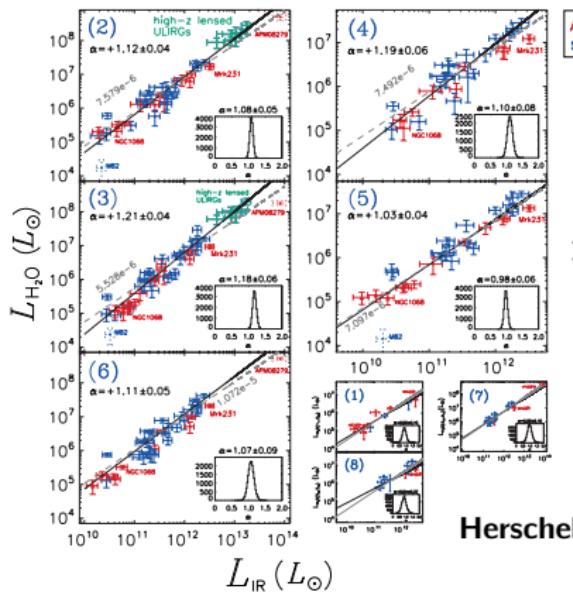
e.g., in Mrk 231: *González-Alfonso+2010; APM08279: van der Werf +2011; Lis+2011; Bradford+2011; HLSJ091828: Combes+2012; HFLS3: Riechers+2013; ...*



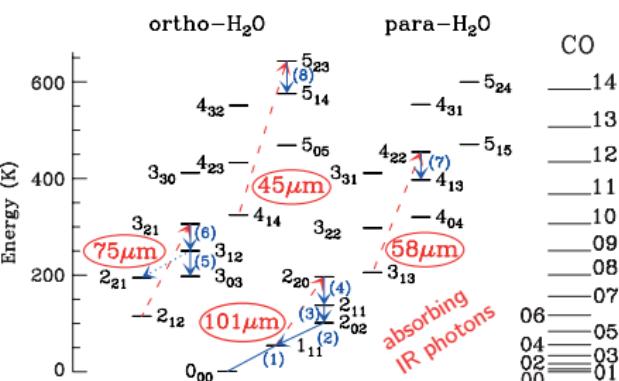
H_2O : a powerful diagnostic tool !

- 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 $\text{H}_2\text{O}/\text{CO} \sim 0.3\text{-}1$ (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_{warm} , opacity, ...

A first systematic study of submm H_2O in local galaxies



AGN-dominated
star-forming-dominated



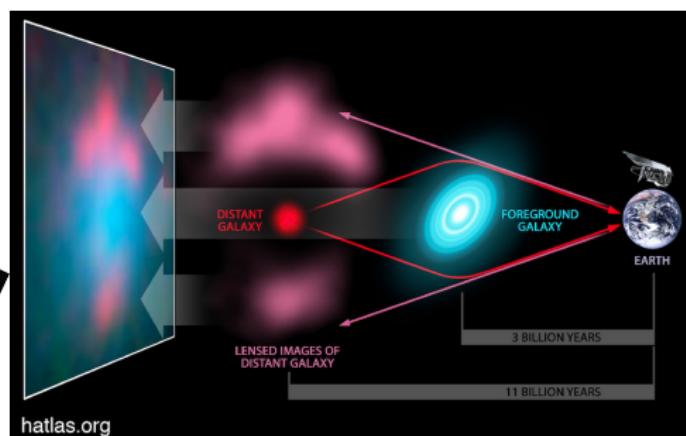
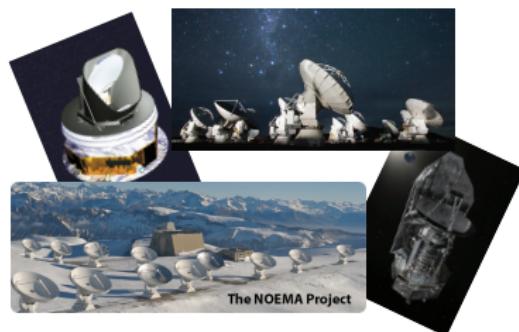
Herschel SPIRE/FTS archive survey: Yang et al., 2013
(see also Master Thesis of Chentao Yang, 2013)

- First systematic study of submm rotational H_2O emission lines in local infrared galaxies (45 out of 176)
- $L_{\text{H}_2\text{O}}$ is roughly proportion to L_{IR} : Confirm the importance of IR pumping for the submm H_2O excitation

$\text{H}_2\text{O}/\text{H}_2\text{O}^+$ emissions in high-redshift lensed ULIRGs

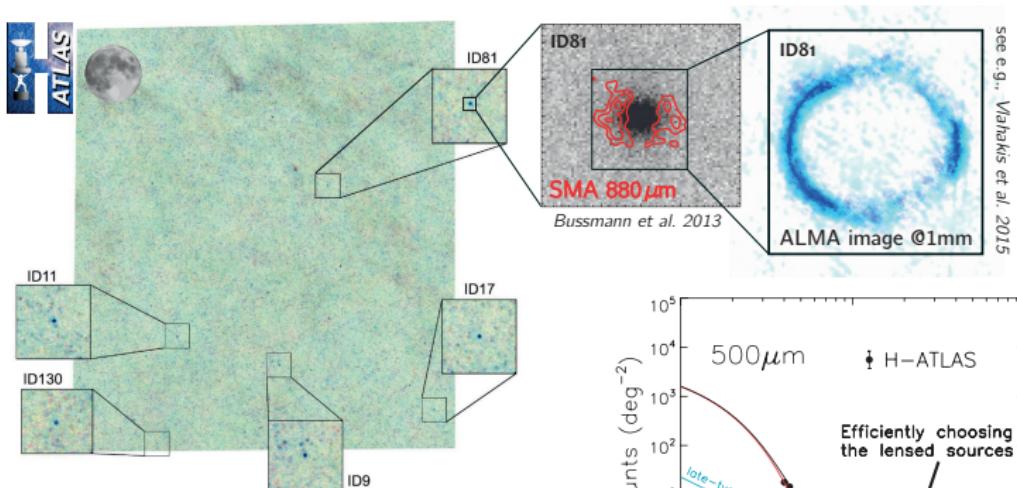
How to observe the submm rotational H_2O lines?

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



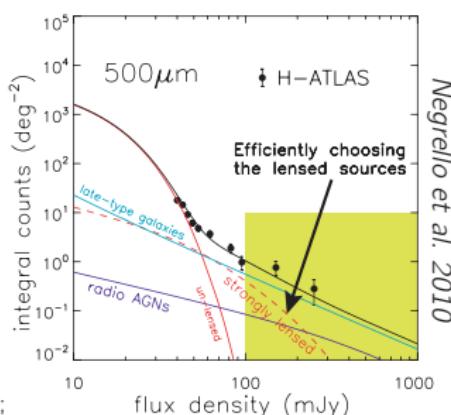
H_2O/H_2O^+ emissions in high-redshift lensed ULIRGs

Finding the strongly lensed high-redshift ULIRGs



Herschel-ATLAS (Eales et al. 2010):

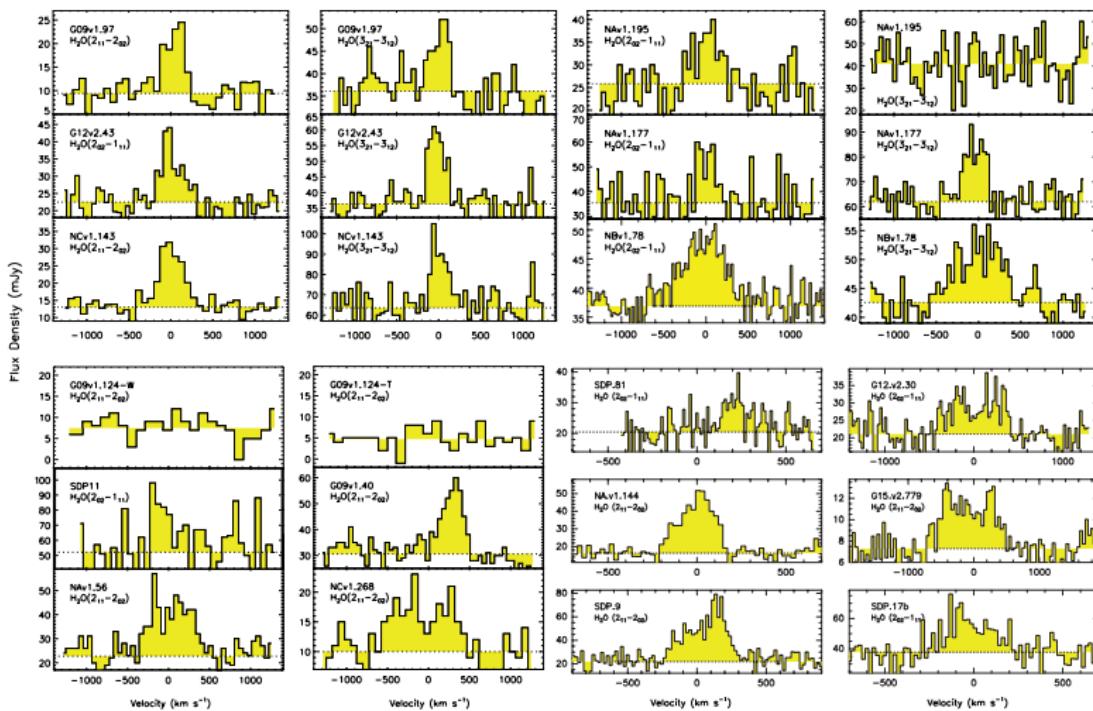
- Widest area survey with *Herschel* (570 deg^2);
- Covering 5 bands from $100 \mu\text{m}$ to $500 \mu\text{m}$;
- **Selecting** strongly lensed candidates by $S_{500\mu\text{m}} > 100 \text{ mJy}$;
- Determining the **redshifts** by follow-up CO observations;
- Follow-up imaging observations for building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



H_2O/H_2O^+ emissions in high-redshift lensed ULIRGs

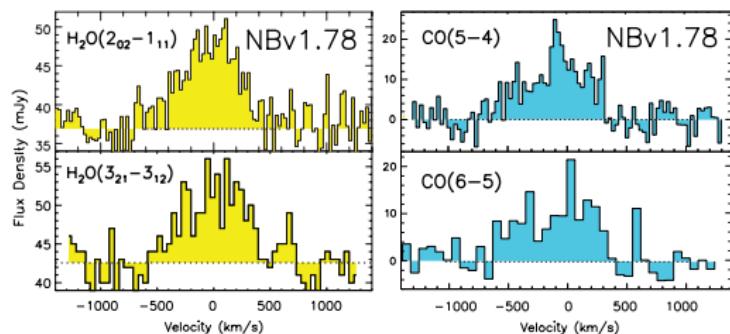
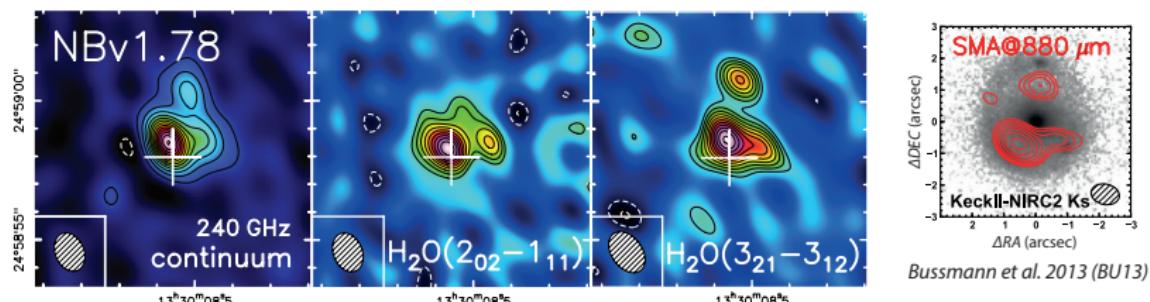
H_2O detections in the *Herschel* high-z lensed ULIRGs

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



H_2O lines of high-redshift lensed ULIRGs (an example)

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



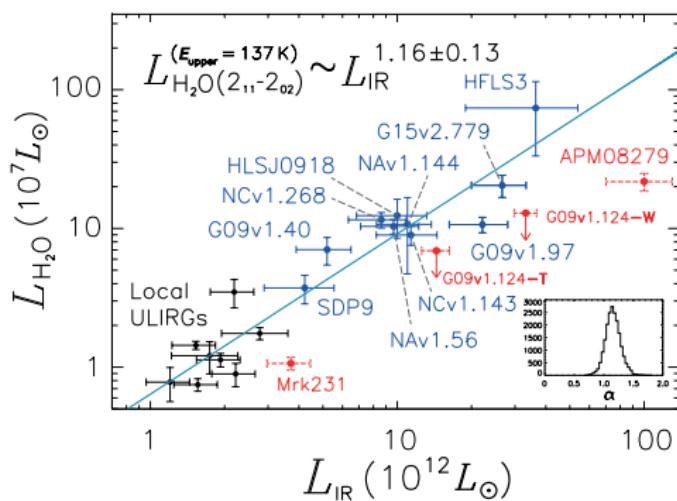
21 good H_2O emission line detections in 16 high-z ULIRGs

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

H_2O/H_2O^+ emissions in high-redshift lensed 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



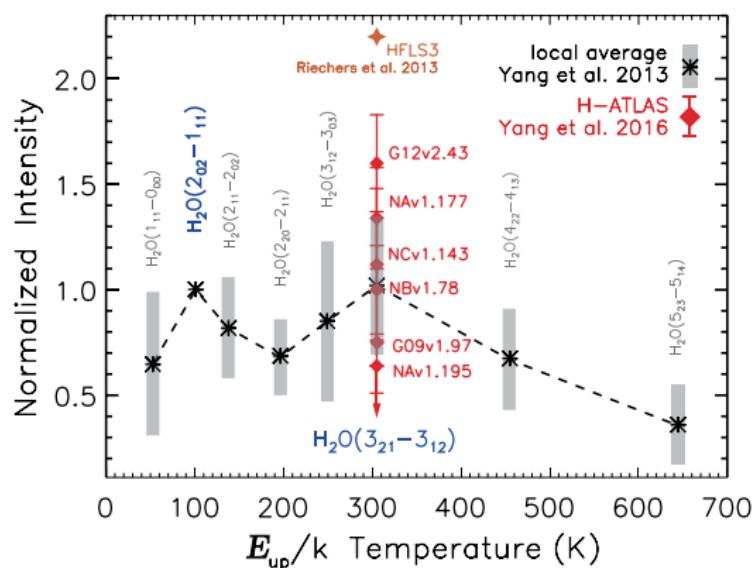
- L_{IR} and L_{H_2O} are roughly proportional
 - Can be explained by the infrared pumping model (González-Alfonso et al. 2014)
- Good tracer of the IR radiation field
 - No AGN signature (mid-IR and radio)
--> Tracing the **IR radiation fields connected to star formation**

H_2O Spectral Line Energy Distribution (SLED)

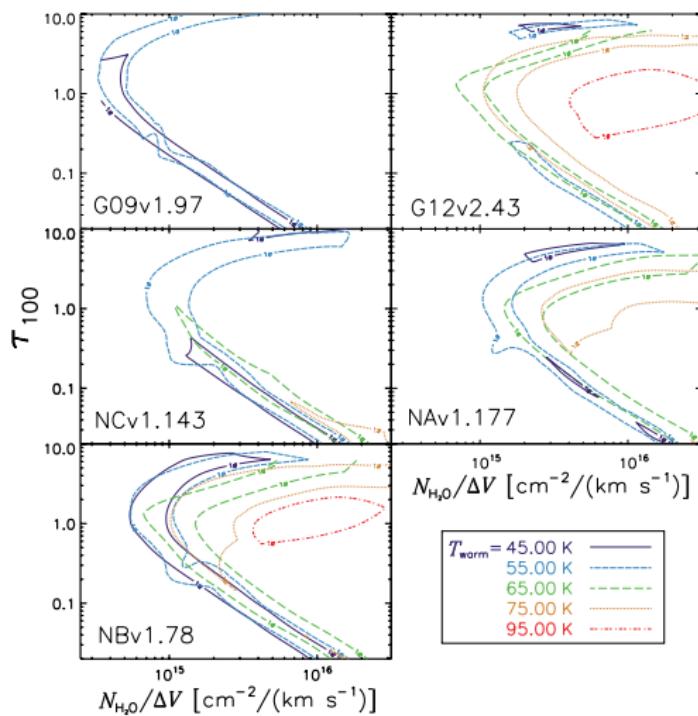
Exploring the H_2O excitation in *Herschel* high-redshift ULIRGs, Yang et al., 2016

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

- Large variation in the relative strength of higher-excitation line $\text{H}_2\text{O}(3_{21}-3_{12})$.
- Indicating various properties of infrared radiation fields.
- Higher excitation level ($J \geq 4$) H_2O lines are needed in excitation modelling.

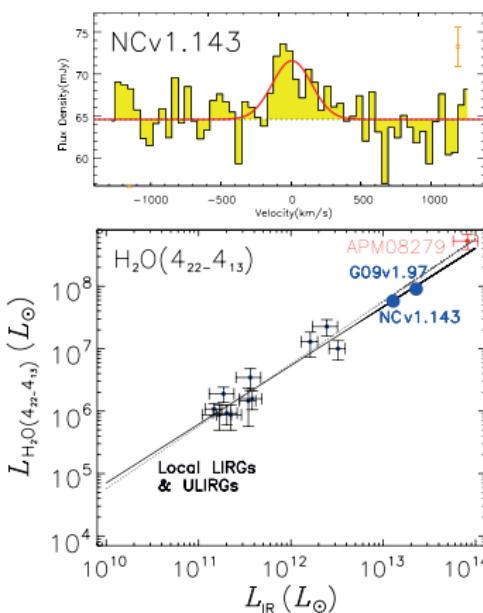
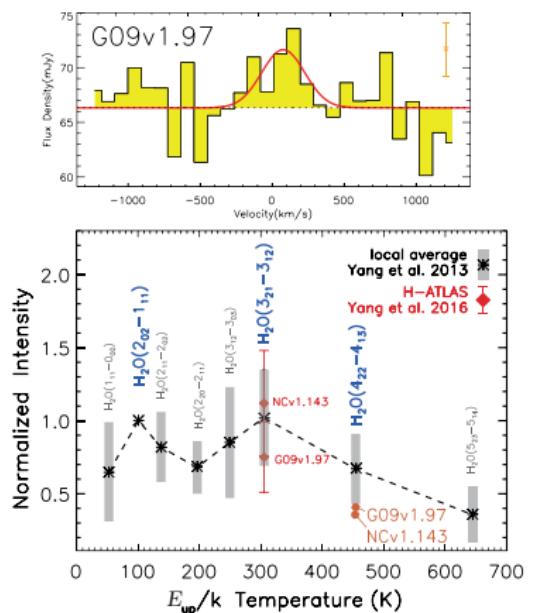


Modelling the H_2O gas excitation



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 ($T_{\text{warm}} \sim 45\text{--}75$ K).
- Strong degeneracies: $J \geq 4$
 H_2O lines are needed for better constraints
(ongoing project).

On-going observations of $J = 4 \text{ H}_2\text{O}$ emission line via NOEMAOn-going observations of $J = 4 \text{ H}_2\text{O}$ lines using NOEMA $L_{\text{IR}} - L_{\text{H}_2\text{O}}$ correlation and further constraining of the IR pumping model

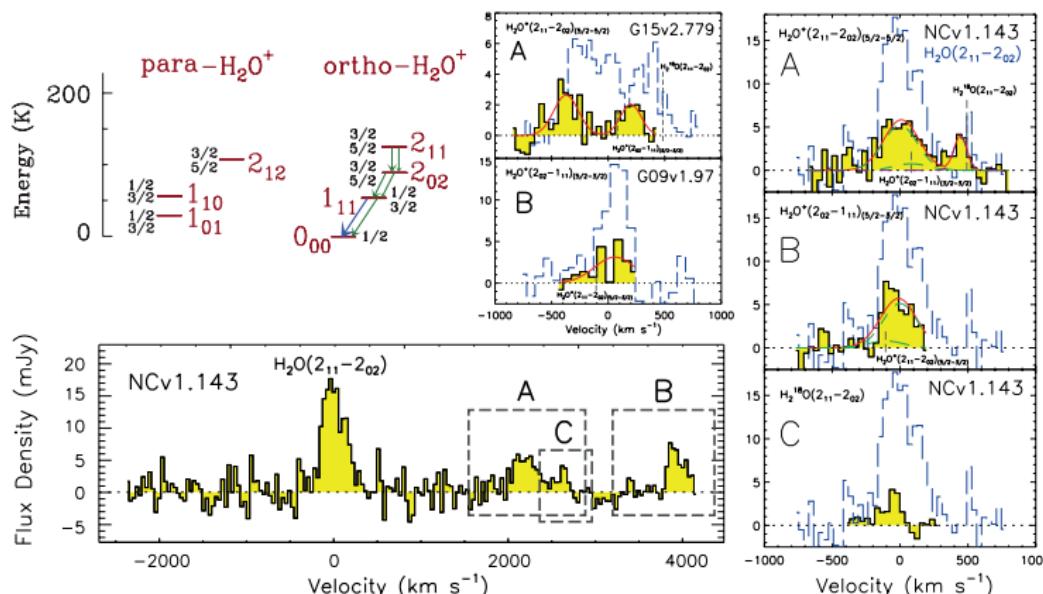
Preliminary results, Yang et al. in prep.

- $J = 4 \text{ H}_2\text{O}$ is important for constraining the H_2O excitation modelling.

Understand the ionisation rate and H_2O formation via H_2O^+

H_2O^+ emission in the high-redshift ULIRGs

Shedding light on the chemistry of $\text{H}_2\text{O}/\text{H}_2\text{O}^+$ (Yang et al., 2016)

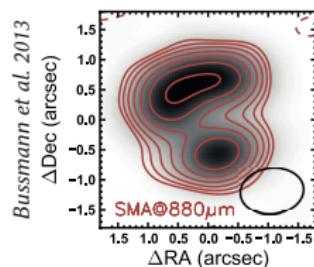
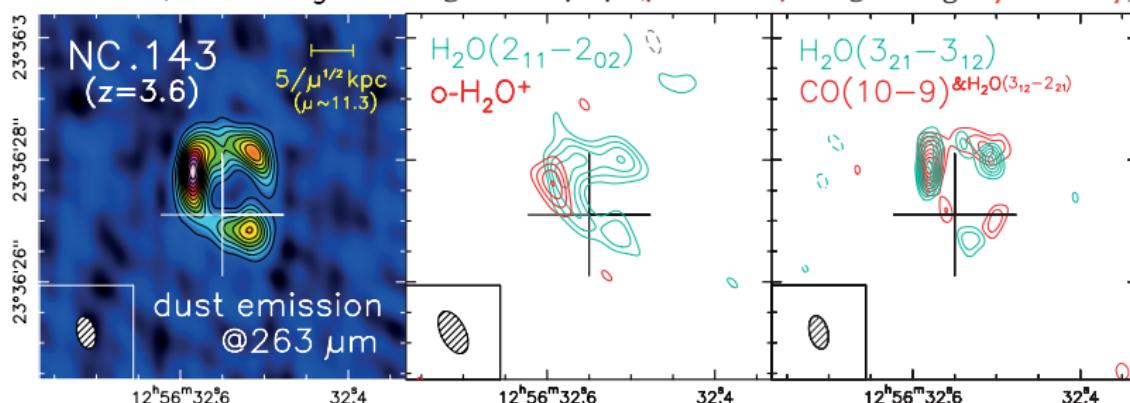


- $\text{H}_2\text{O}^+/\text{H}_2\text{O} \sim 0.3$: cosmic rays from star formation may drive the H_2O^+ formation (Meijerink et al. 2011).
- H_2O formation is likely to be dominated by the ion-neutral route and/or an undepleted chemistry.

On-going high angular resolution imaging of H_2O and dust via NOEMA

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.
- $L_{\text{H}_2\text{O}} \sim L_{\text{IR}}^{1.1-1.2}$, 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.
- $\text{H}_2\text{O}^+/\text{H}_2\text{O}$ 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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