H_2O Emission in Ultra-Luminous Infrared Galaxies at z~2-4

yangcht@pmo.ac.cn

Chentao Yang [1,2,3], Alain Omont[2,4], Alexandre Beelen[3], Eduardo González-Alfonso[5] and Yu Gao[1] on behalf of *Herschel*-ATLAS* and IRAM Teams

1. Purple Mountain Observatory; 2. Institut d'Astrophysique de Paris, CNRS; 3. Institut d'Astrophysique Spatiale; 4. UPMC Univ. Paris 06; 5. Universidad de Alcalá

Abstract

Herschel observations of local infrared bright galaxies have revealed a rich spectrum of submillimeter H_2O rotational emission lines up to upper level energy of $E_U/k = 642$ K. H_2O is found to be the second strongest molecular emitter after CO in the submillimeter band, sometimes with comparable intensity. The strong H_2O lines provide a unique diagnostic for a totally different regime than the CO usual lines considering its very different excitation process. Using IRAM PdBI, we have extended our H_2O detections with 15 more lines in 11 high-z lensed Ultra-Luminous Infrared Galaxies (ULIRGs, five of them have both para J=2 and ortho J=3 H_2O detected) discovered by *H*-ATLAS. The total number of the H_2O detected galaxies in our sample is now 17. As in the local ULIRGs, the intensity of the high-z H_2O lines are strong, $\gtrsim 0.5$ of the mid-J CO lines. The CO detected using IRAM 30m telescope in some of the sources have similar line profiles as H_2O, indicating their similar spatial distributions considering the differential lensing. The intrinsic H_2O line luminosity L_{H_2O} increases slightly faster than linearly with the intrinsic infrared (IR) luminosity, $\propto L_{IR}^{1.1\text{-}1.2}$, for the J=2 (E_U/k~100 K) and J=3 (E_U/k~300 K) H_2O lines. This implies that IR pumping is important for the H_2O excitation in these sources. Also, the ratio H_2O J=2/J=3 varies in those high-z ULIRGs, likely reflecting different physical conditions, e.g., dust temperature and far-IR opacity. Besides H_2O, we have also detected H_2O^+ and $H_2{}^{18}O$ in some of the galaxies. The intensity ratios together with the isotopic ratio suggest that the H_2O lines are well saturated while the H_2O^+ and $H_2{}^{18}O$ lines are likely to be optically thin. However, high resolution study is still needed for revealing the spatial distribution of H_2O emission within.

Sample selection and observation

How to observe H_2O?

- Local universe: space telescopes like *Herschel* (See our poster **S315p.186** for a local survey)
- Redshifted (high-z) line observation with high sensitivity: **gravitational lensing!**
- Source selection:
  - Select the bright **lensed** ULIRGs from *H*-ATLAS catalog.
  - The redshifts are secured by the previous CO detections via CARMA (Riechers et al. in prep.), GBT (Harris et al. 2012; Lupu et al. 2012) and PdBI (Krips et al. in prep.). The redshift distribution is shown in Fig. 1.
  - Lensing properties are well described in Bussmann et al. (2013).

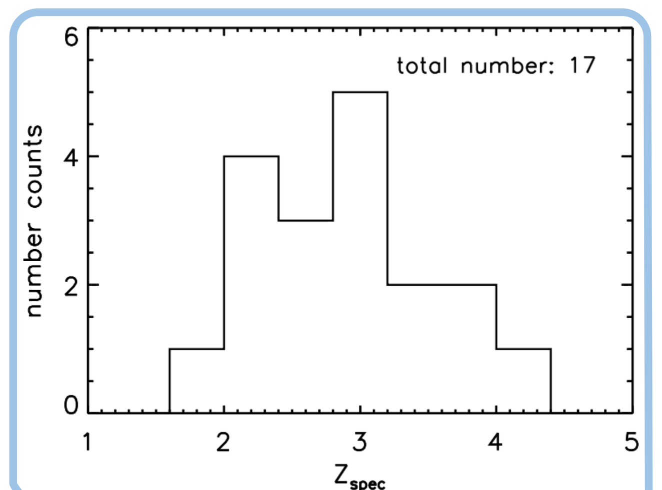


Fig. 1. Spectroscopy z distribution of the galaxies in our sample.

- The chosen sources (**17 in total**) and H_2O lines (as shown in Fig. 2):
  - Sources with both **para J=2** and **ortho J=3 H_2O** lines observed:
    - ***G****AMA field sources*: *G09v1.97, G12v2.43*
    - ***N****orthern Galactic Pole field sources*: *NBv1.78* (J=3 H_2O only) *NCv1.143, NAv1.195, GAv1.177*
  - Sources with only **para J=2 H_2O** observed:
    - ***S****cience* ***D****emonstration* ***P****hase filed*: *SDP11*
    - *NCv1.268, NAv1.56*
    - *G09v1.124, G09v1.40*
  - **Previous** detected sources in Omont et al. (2013):
    - *SDP81, SDP9, SDP17b*
    - *G12v2.30, G15v2.779*
    - *NAv1.144, NBv1.78* (J=2)
  - Additional observations:
    - CO lines via IRAM 30m
    - Dense gas via PdBI

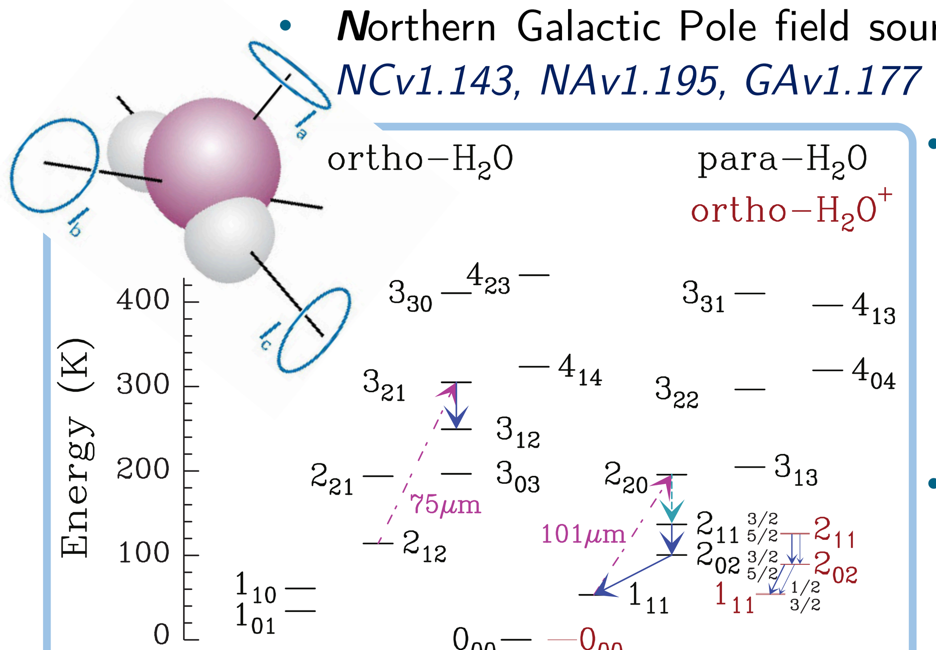


Fig. 2. H_2O and H_2O^+ energy level diagram shown in black and red color, respectively. Blue arrows are the H_2O emission lines we have observed in this work. Pink dashed lines show the H_2O IR pumping paths in our model, with the labeled wavelength.

Results

- **H_2O emission line is strong**: we have robustly detected **almost all** the H_2O lines with high signal to noise ratios. However, the non-detections are $H_2O(2_{11}-2_{02})$ in G09v1.124 and $H_2O(3_{21}-3_{12})$ in NAv1.195. Our sources represent **close to 80%** of the current high-z detections of the submillimeter H_2O emission.
- **As an example**, the images of the H_2O lines and the underlying dust continuum emissions from one of the 17 sources, NBv1.78, are shown in Fig. 3. And Fig. 4 shows its H_2O spectra together with the CO lines.

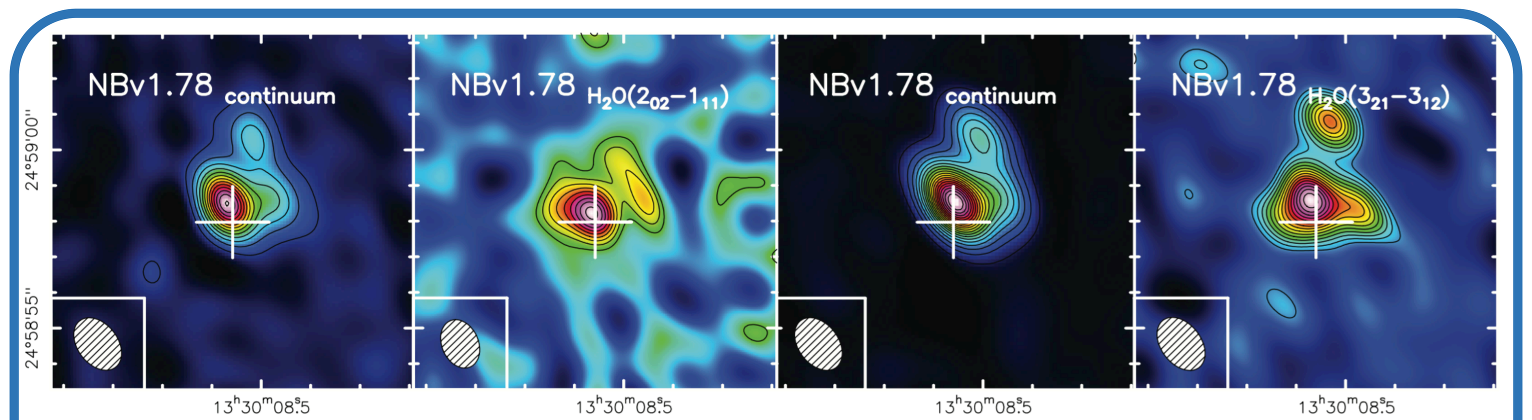
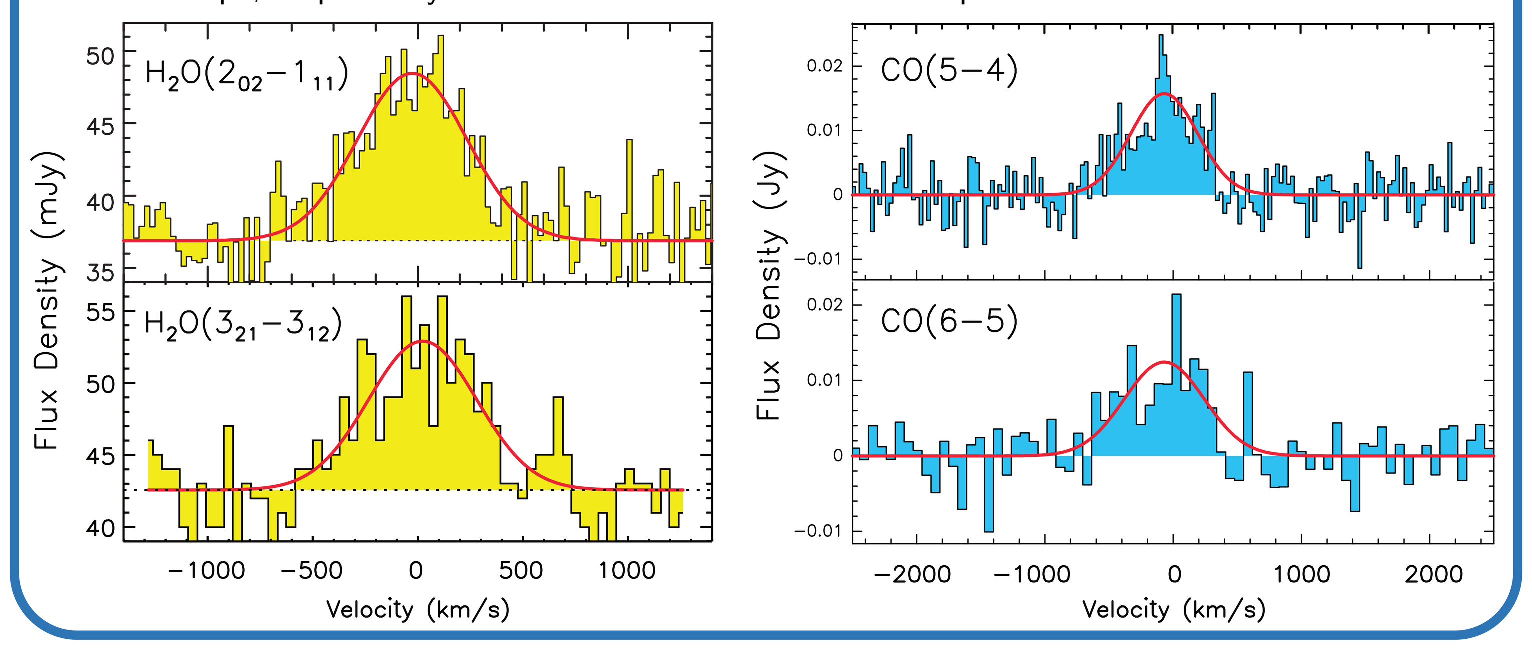


Fig. 3. ***Above:*** Images of the H_2O emission and the corresponding continuum emission in NBv1.78. The contours of the continuum start from 6σ in step of 10σ. And for the H_2O lines, they start from 3σ in step of 1σ. The 1σ contour for the continuum (mJy/beam) and H_2O emission (Jy km s^{-1}/beam) in NBv1.78 are as follows: $H_2O(2_{02}-1_{11})$ (0.28/0.30), $H_2O(3_{21}-3_{12})$ (0.21/0.29).

Fig. 4. ***Below:*** The H_2O (yellow) and CO (blue) spectra of NBv1.78 obtained by PdBI & IRAM 30m telescope, respectively. Red lines are the fitted Gaussian profiles.



- The H_2O emission has **similar spatial distribution** as the dust emission, especially for the higher-J H_2O lines, being consistent with IR pumping.
- Comparing with mid-J CO lines, the H_2O lines **have similar line profiles**. Thus, they are likely **tracing similar gas structures**.
- We find the H_2O and IR luminosity **are roughly proportional** (Fig. 5).
- Submillimeter H_2O excitation is **dominated by IR pumping**. Therefore, unlike CO rotational lines, it is **a unique diagnostic of strong local far-IR radiation field.**

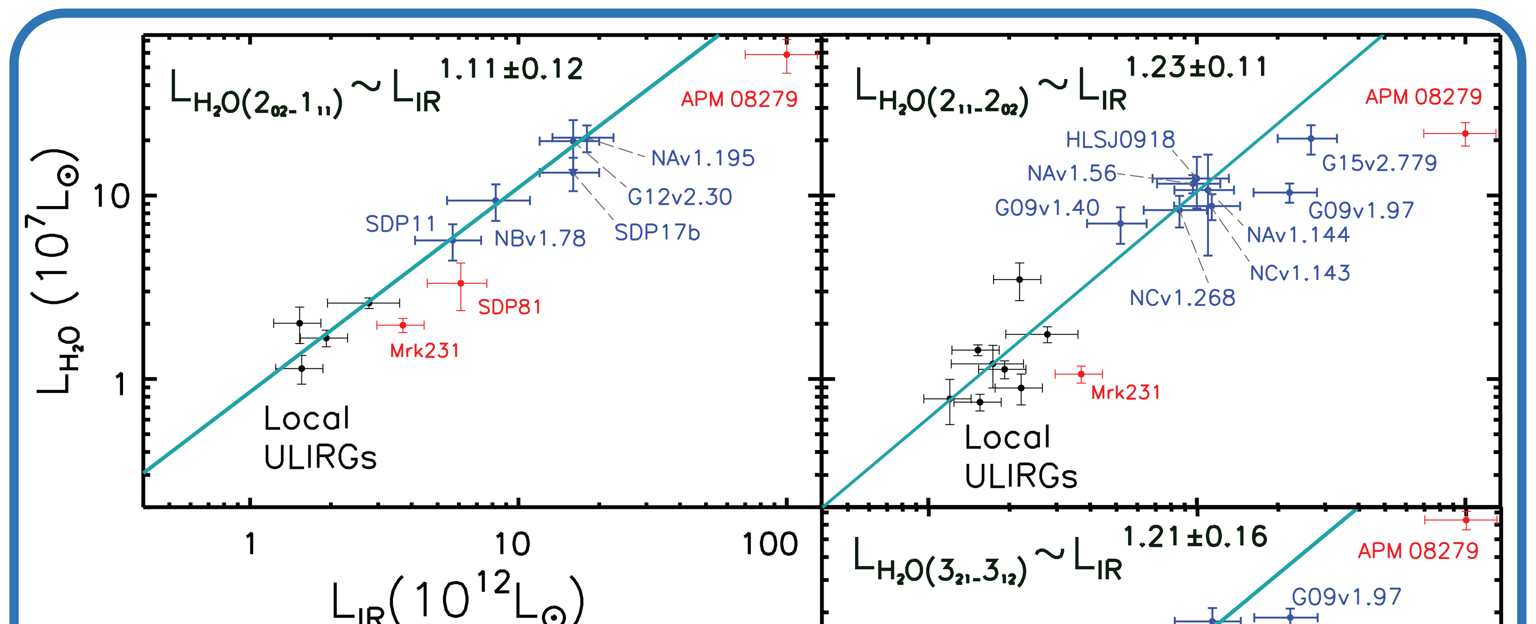
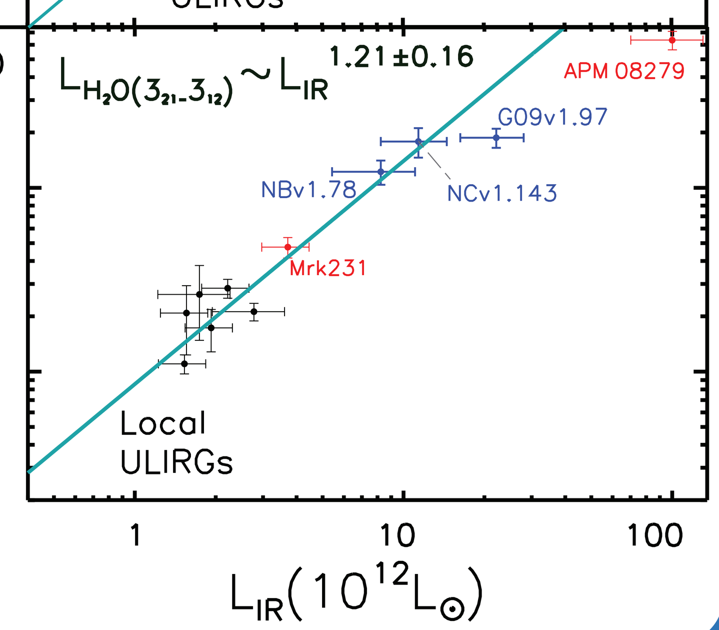


Fig. 5. The correlation between the intrinsic H_2O and IR luminosity for $H_2O(2_{02}-1_{11})$, $H_2O(2_{11}-2_{02})$ and $H_2O(3_{21}-3_{12})$. The black dots represent the local ULIRGs, and the blue dots are the high-z lensed ULIRGs in this work, together with HLSJ 091828.6+514223 from Combes et al. (2012), while the red dots have been excluded from the fit (including the QSO APM 09279+5455 from literatures). Light blues lines are the χ^2 fit results. The slopes are shown in the upper left.



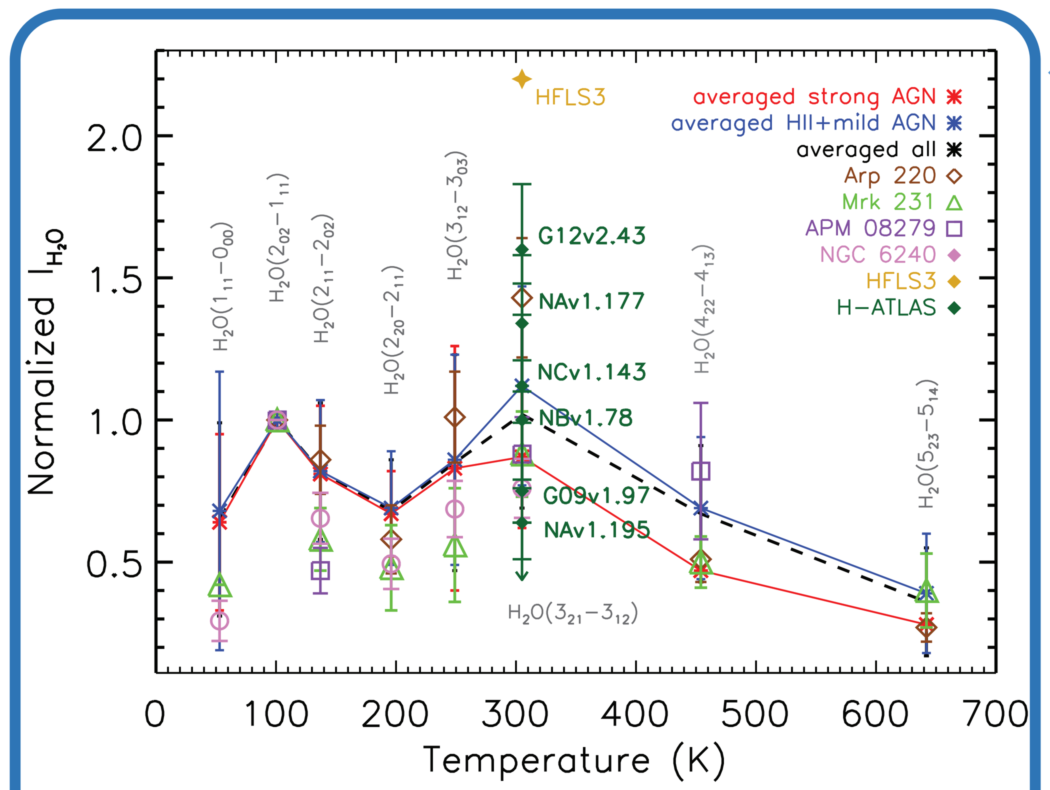


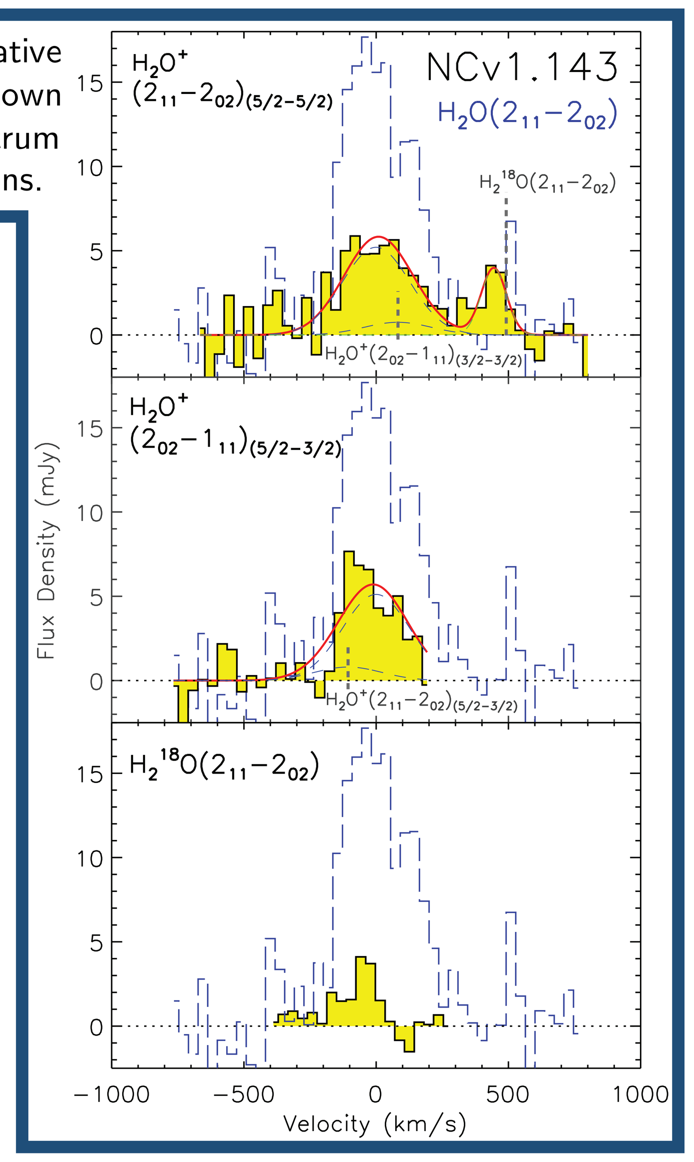
Fig. 6. The H_2O intensities (Jy km s^{-1}) distribution normalized by $(2_{02}-1_{11})$ developed from Yang et al. (2013). Dash lines represent the averaged ratios of the local galaxies. Dark green diamonds are the high-z lensed galaxies from this work. And HFLS3 is a unlensed high-z galaxy from Riechers et al. (2013).

H_2O *SLED*

The ratio $(3_{21}-3_{12})/(2_{02}-1_{11})$ **varies in a large range:** from <0.67 in NAv1.195 up to 2.2 in HFLS3. This difference may represent their intrinsic different physical condition of the local IR radiation fields, if differential lensing is negligible. With a careful H_2O excitation modelling (using the method from G-A14) for 5 sources with both J=2 & J=3 lines detected, we find that **their intensity ratio is sensitive to the dust temperature and continuum opacity in the far-IR**. However, more transitions are needed for better constrains on opacity and H_2O column density.

Detection of H_2O^+ lines

Fig. 7. The detections of H_2O^+ and the tentative detection of $H_2{}^{18}O$ emission in NCv1.143 as shown by the yellow spectra in each panel. H_2O spectrum has been overlaid on each spectrum as comparisons.



First **detections of H_2O^+ emission in the high-z lensed galaxies**:

- We have detect $H_2O^+(2_{11}-2_{02})$ $J_{5/2-5/2}$ in NCv1.143 (Fig. 7) and G15v2.779; and $(2_{02}-2_{11})J_{5/2-3/2}$ in NCv1.143 (Fig. 7) and G09v1.97.
- Tentative detection of J=2 $H_2{}^{18}O$ (Fig. 7, bottom panel) needs to be confirmed with more sensitive observation.
- Analysis of the line ratios among H_2O, H_2O^+ and $H_2{}^{18}O$, together with the abundance ratios suggests that **H_2O are well saturated while the H_2O^+ & $H_2{}^{18}O$ are likely to be optically thin.**

Prospect

- H_2O is strong and suitable for systematic high-z studies using the current facilities like PdBI and ALMA.
- By combining the analysis of CO lines (our ongoing project), we will have a fully view of the physical condition of the molecular gas, helping us to study varies processes in ISM of the very early universe.
- ALMA can easily detect H_2O^+ and $H_2{}^{18}O$ lines, which are important for both dynamical analysis and astrochemistry studies at high-z.

References

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