Submillimeter H_2O Emission in Infrared Galaxies Near and Far

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We conduct **the first systematic study** of the submillimeter H_2O rotational emission lines in the infrared galaxies from local to high redshift observed by FTS/*Herschel* and PdBI. Among the 176 local galaxies, 45 have at least one H_2O emission line detected. H_2O is found to be the strongest molecular emitter after CO in the submillimeter band. For the five most detected H_2O lines, the luminosity is near-linearly correlated with L_{IR} no matter strong AGN signature is present or not. Although the slope turns out to be slightly steeper when z~2-4 ultra-luminous infrared galaxies (ULIRGs) are included, the correlation is still close to linear. We find that L_{H_2O}/L_{IR} decreases with increasing infrared color f_{25}/f_{60}, but nearly no dependence on f_{60}/f_{100}, possibly indicating that very warm dust contributes little to the excitation of submillimeter H_2O lines, and this is consistent with later modelling studies. The average spectral line energy distribution (SLED) of entire sample is consistent with individual SLEDs and the IR pumping dominated excitation model, showing that the strongest lines are $H_2O(2_{02}-1_{11})$ and $(3_{21}-3_{12})$. And their intensity ratio varies within a large range. Besides H_2O, we have also detected several H_2O^+ emission in 12 local and 3 high-z galaxies, and their luminosity is proportional to the corresponding H_2O line luminosity.

ABSTRACT

Observation and data

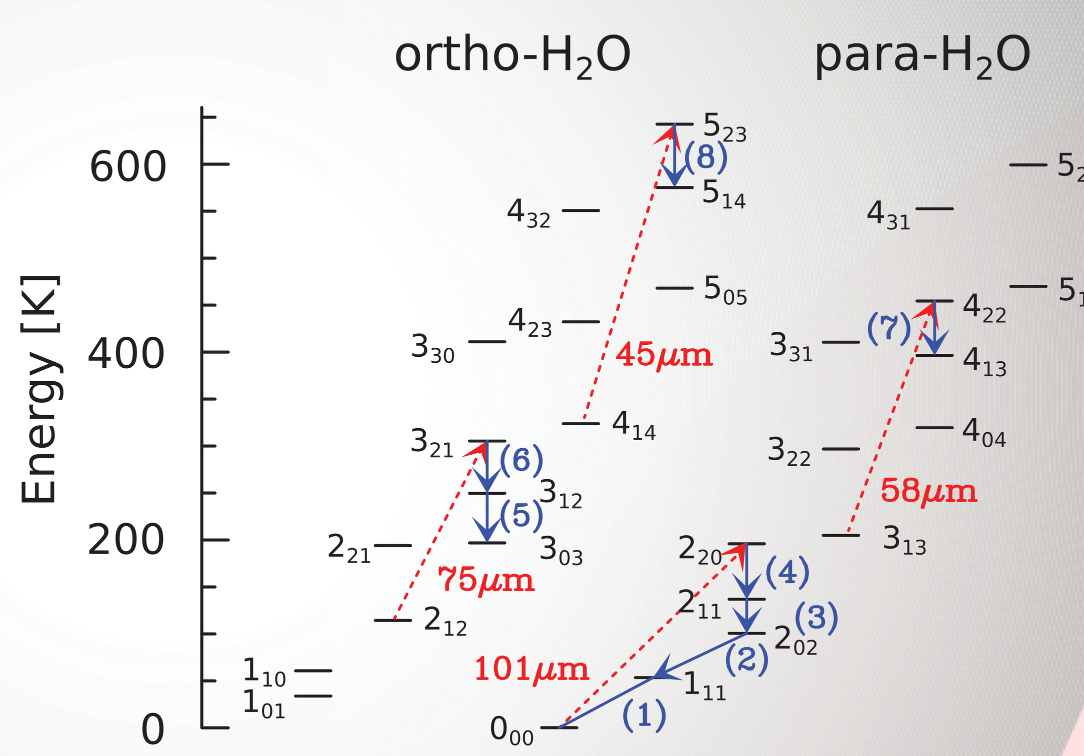

Fig. 1. H_2O energy level diagram. The red dashed lines indicate the main IR-pumping paths and the blue lines indicate the transition we observed in this work with the index number of H_2O line we used in the following discussion.

H_2O is abundant and a very important Oxygen carrier in ISM. And only with space telescope like *Herschel* we can study the rich submillimeter spectrum of H_2O in the local universe.

- **Sample selection and data:** We use *Herschel* Science Archive SPIRE/FTS (spectral) and PACS (photometric) public data. We have selected 176 nearby galaxies available and checked each for detection.
  - **Data reduction:** HIPE, Scanamorphos and IDL. L_{IR} is from Sanders et al. (2003), scaled with H_2O line beam using PACS images.
    - 8 observed H_2O (**index 1-8**) lines as shown in Fig. 1.

L_{H_2O}-L_{IR} Correlation

A near-linearly correlation between L_{H_2O} and L_{IR} is found for the 8 submillimeter H_2O lines (Fig. 2):

$$\log L_{H_2O} = \alpha \log L_{IR} + \beta$$

The correlation is valid from local to high-z galaxies, from 10^{10} to 10^{14} $L_\odot$ in terms of L_{IR}, and from 10^5 to 10^9 $L_\odot$ in terms of L_{H_2O}, having a large dynamic range.

The correlation has no obvious difference between **AGN** & **starburst** dominated galaxies as shown in Fig. 2. This correlation can be simply explained as a result of IR-pumping. The H_2O excitation is dominated by IR-pumping, and closely correlated with local IR field, the warm dust emission. It can not tell the difference between starburst and AGN powered dust emission.

As in Fig. 4, we find L_{H_2O}/L_{IR} decreases with increasing f_{25}/f_{60}, but see no dependence on f_{60}/f_{100}, possibly indicating that very warm dust contributes little to the excitation of the submillimeter H_2O lines.

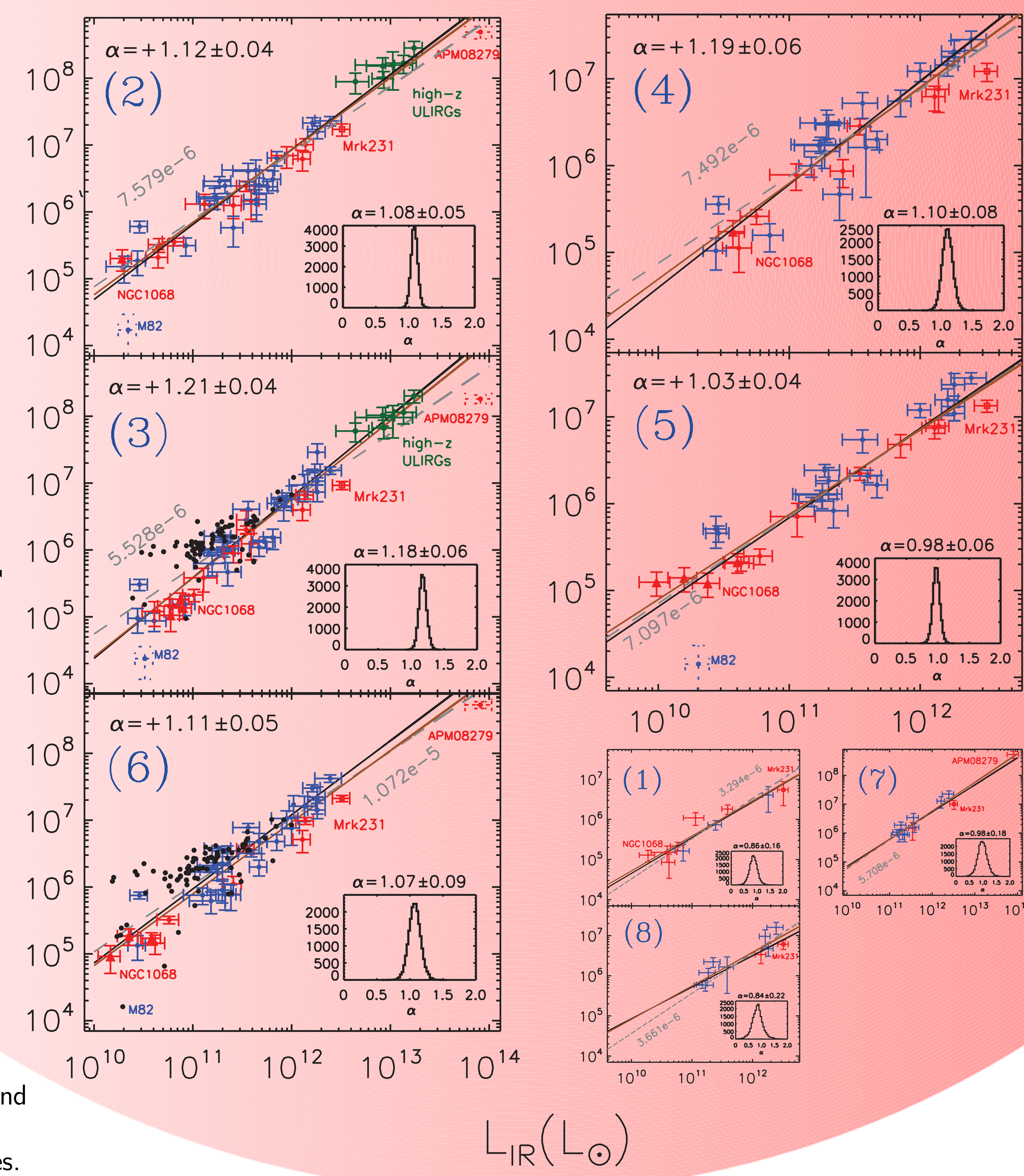

Fig. 2. Correlation between H_2O and the corresponding IR luminosity. The fitted lines by *MPFIT* and *LINMIX_ERR* are shown in black and brown lines, respectively, while the gray lines are the linear fitting with a fixed slope (α = 1). The red, blue, green, and black dots represent strong-AGN, HII+mild-AGN dominated galaxies, high-z ULIRGs, and the upper limits for non-detections, respectively. The solid triangles are the mapping mode data of NGC1068. Mrk231 is marked in red squares. M82 and APM08279+5255, marked with dashed error bars, are excluded from the fitting.

High-z sources?

High-z sources have slightly higher L_{H_2O}/L_{IR} ratios.

Please see our poster *FM15p.02* for more detailed and interesting high-z ULIRGs observation results.

L_{H_2O}-color Correlation

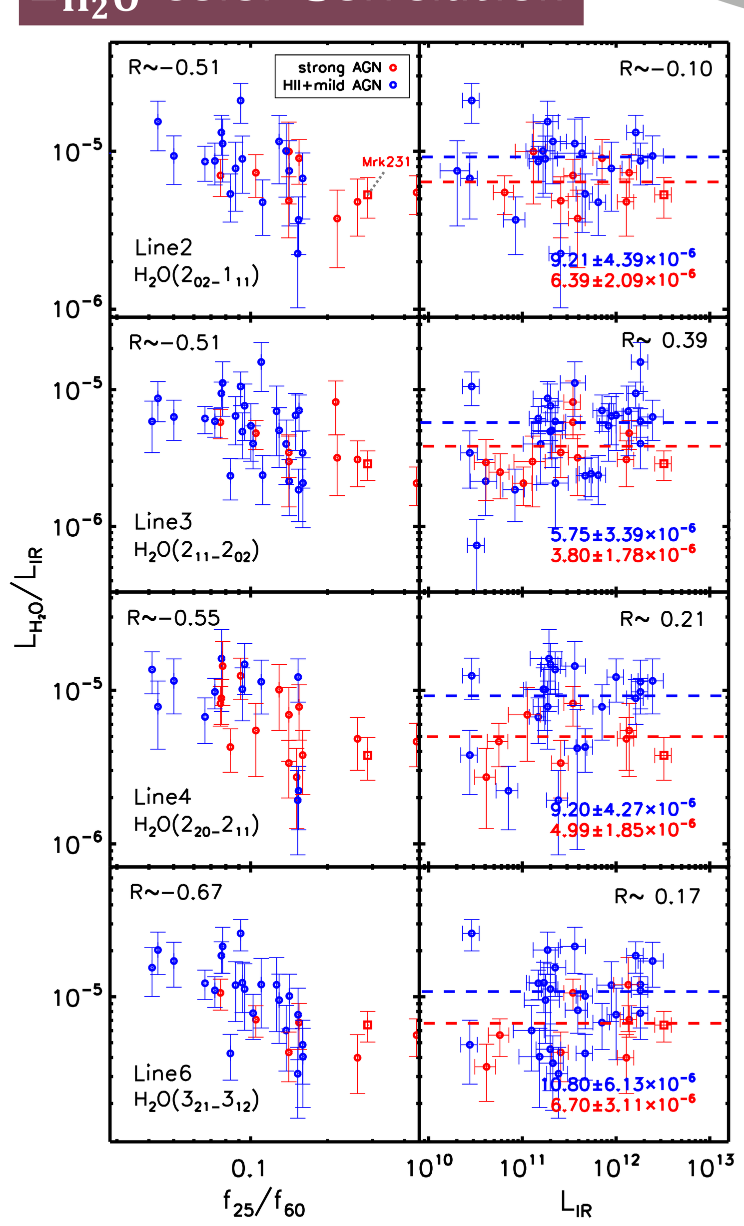

Fig. 4. L_{H_2O}/L_{IR} vs. f_{25}/f_{60} & L_{IR}, respectively. From top to bottom, each row displays the values of line (2)-(4), and (6) as examples. The averaged values of L_{H_2O}/L_{IR} of strong-AGN and HII+mild-AGN dominated sources are shown in red and blue text and dashed lines in the second column. R in each panel is the correlation coefficient. Mrk231 is shown in red squares.

Averaged H_2O SLED

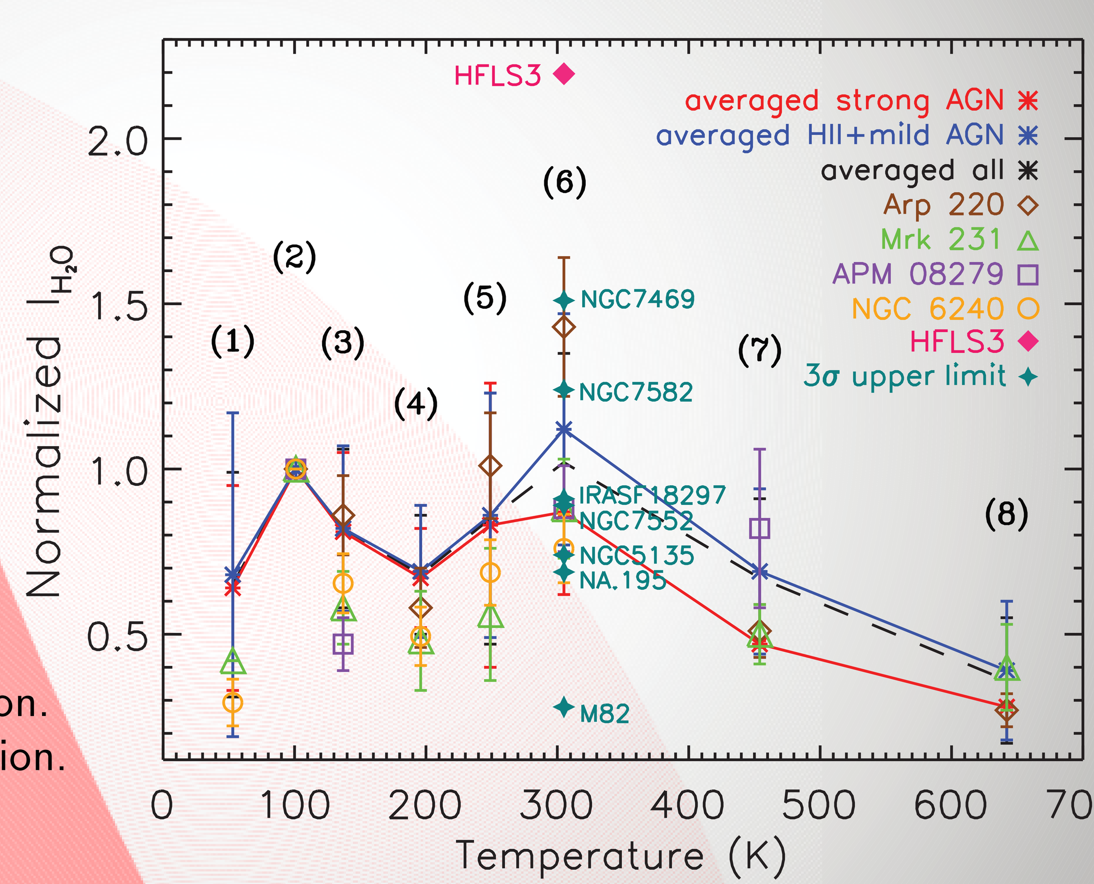

Fig. 3. The $H_2O(2_{02}-1_{11})$ intensity normalized H_2O **S**pectral **L**ine **E**nergy **D**istribution. The black dashed line is the average values of the whole sample, while red and blue points and lines are those of the strong-AGN and HII+mild-AGN dominated ones, respectively. Dark green dots are 3σ upper limits for the non-detections. (See references for the individual sources in Yang et al. 2013).

The individual studies agree well with our averaged SLED. All the H_2O SLEDs show two peaks at line (2) and (6), and the latter is slightly stronger. The explanation for the strong high-lying peak could be that the IR spectral energy distribution (SED) peaks are close to 75 µm which could result in higher IR pumping efficiency considering the possibility of IR pumping at 75 µm (Fig. 1) which is the main power path for H_2O line $(3_{21}-3_{12})$ and $(3_{12}-3_{03})$.

The line ratios (6)/(2) for the non-detected sources are also within range. This ratio could reflect the difference of their local IR fields.

H_2O^+ and $H_2{}^{18}O$ detection

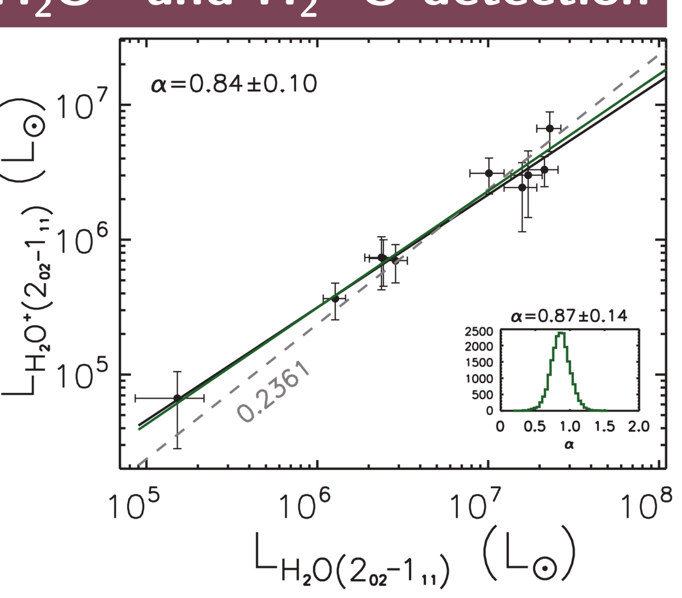

Fig. 5. We have 5 local H_2O^+ line $(1_{11}-0_{00})$, 12 local and 1 high redshift $(2_{11}-2_{02})$ $J_{5/2-5/2}$, 7 local and 3 high-z $(2_{02}-1_{11})$ $J_{5/2-3/2}$, and 3 $H_2{}^{18}O$ $(3_{21}-3_{12})$ lines detected. Both strong-AGN and HII+mild-AGN dominated galaxies are among these detections. We find their luminosities to be **tightly correlated** with those of the related H_2O transitions.

Future works

- By combining the analysis of CO data we can learn the physical properties of different gas components.
- Statistical analysis of the physical properties from the excitation modelling of H_2O and CO for the galaxies near and far.
- Stack analysis for the weak lines such as H_2O^+ and $H_2{}^{18}O$.

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