

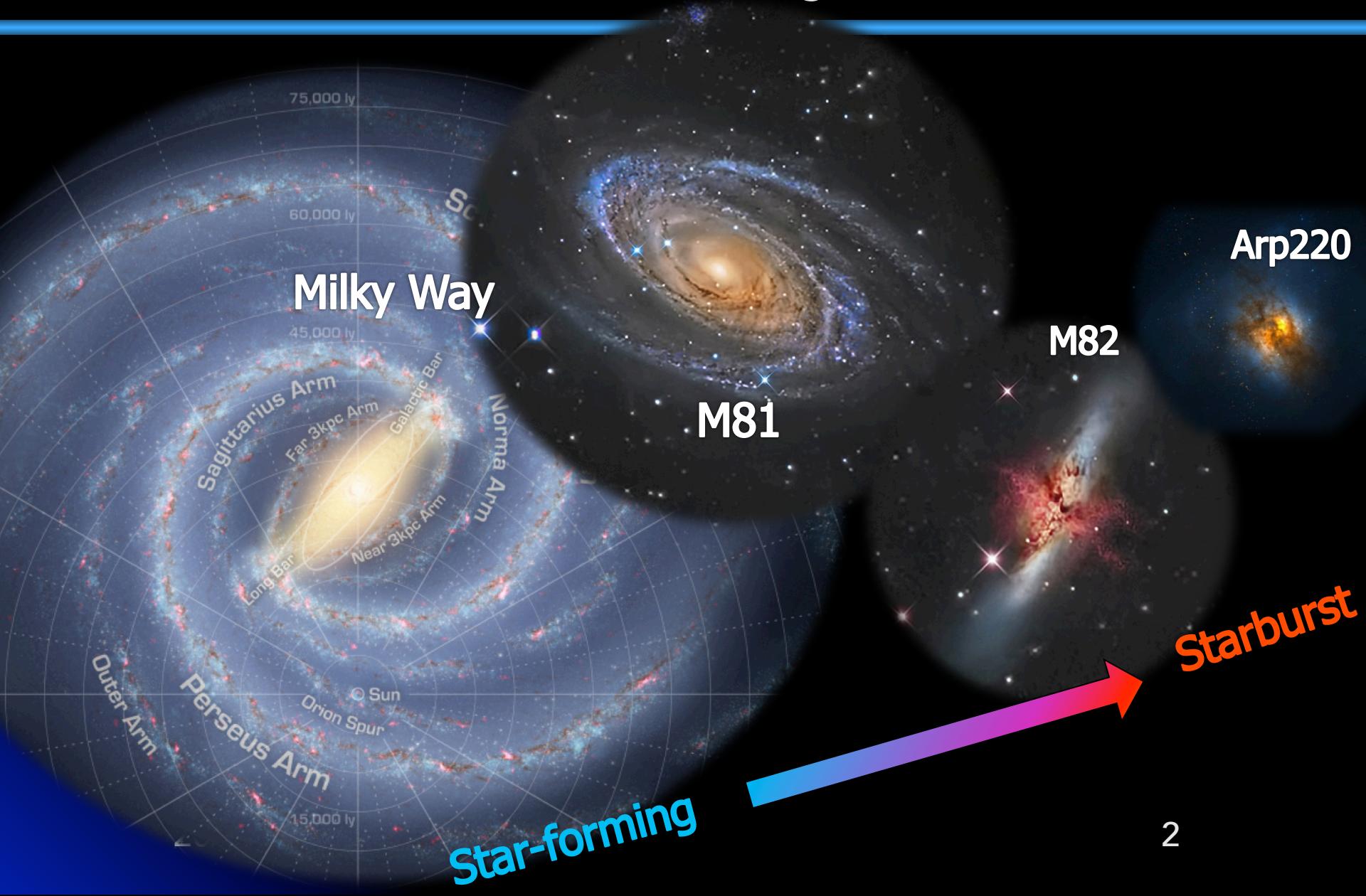
H_2O and Star Formation in Galaxies: An *Herschel* SPIRE FTS Perspective

Contents:
Motivation
Sample & data
 H_2O vs. star formation
Dense gas in galaxies
Summary

2016-04-15

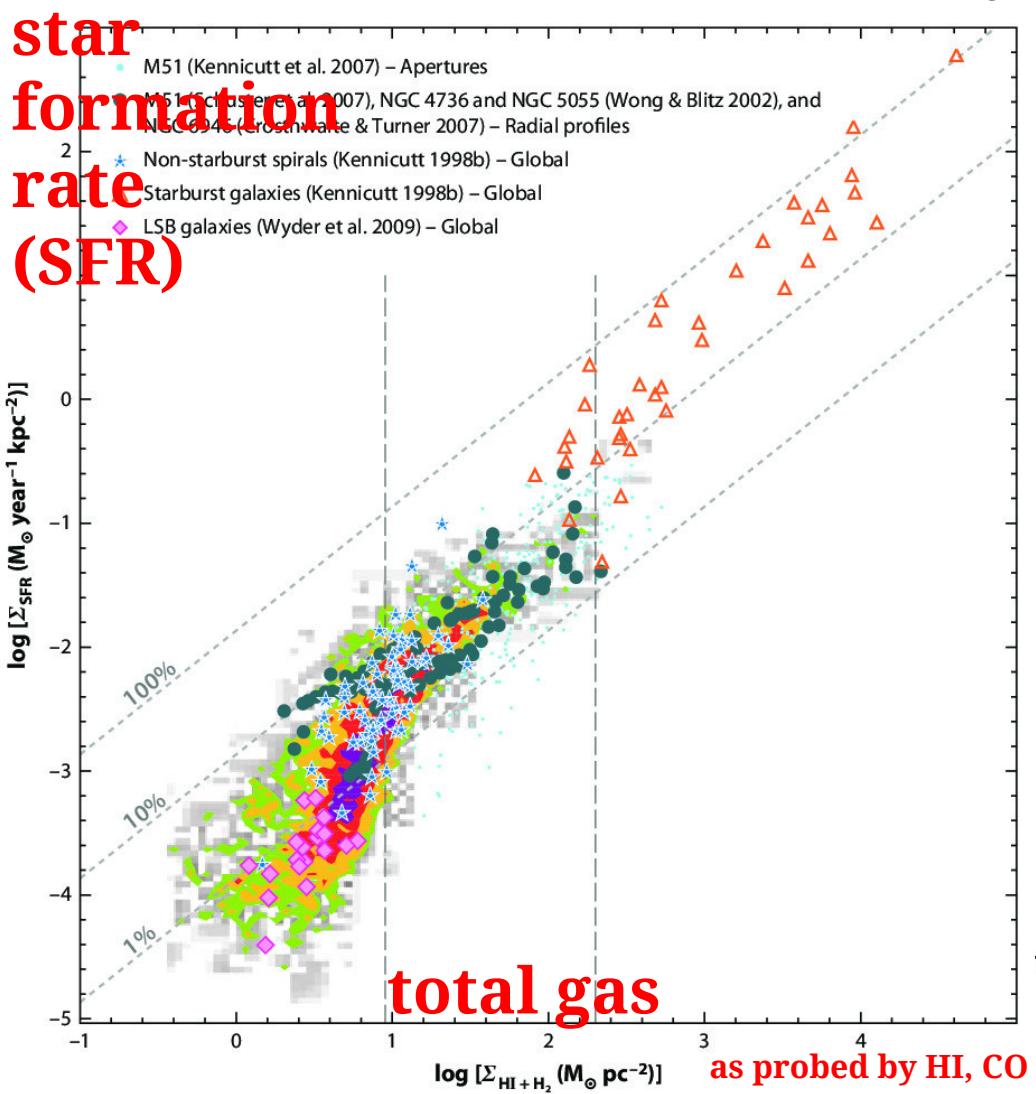
Daizhong Liu &
Yu Gao, Chentao Yang, et al.
Purple Mountain Observatory
dzliu@pmo.ac.cn &
yugao@pmo.ac.cn

Star formation in galaxies



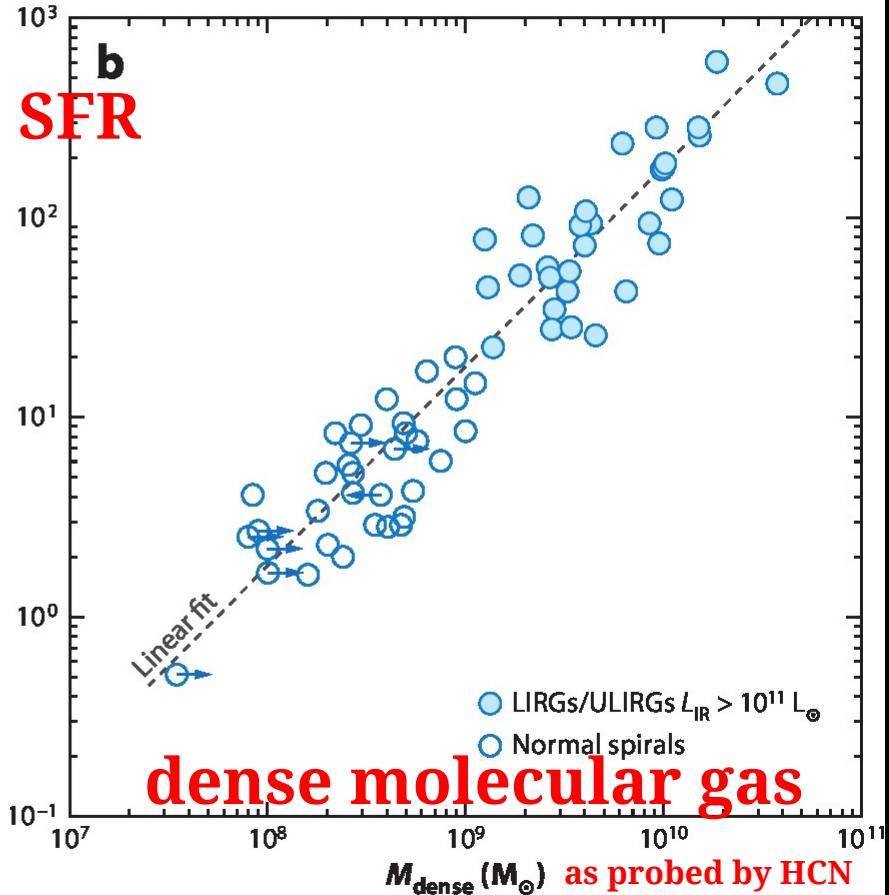
Star formation – molecular gas – dense gas

**star
formation
rate
(SFR)**



total gas

Kennicutt & Evans (2012) Annual Review
see also Kennicutt (1998);
Gao & Solomon (2004)



dense molecular gas

Herschel SPIRE Fourier Transform Spectrometer (FTS)



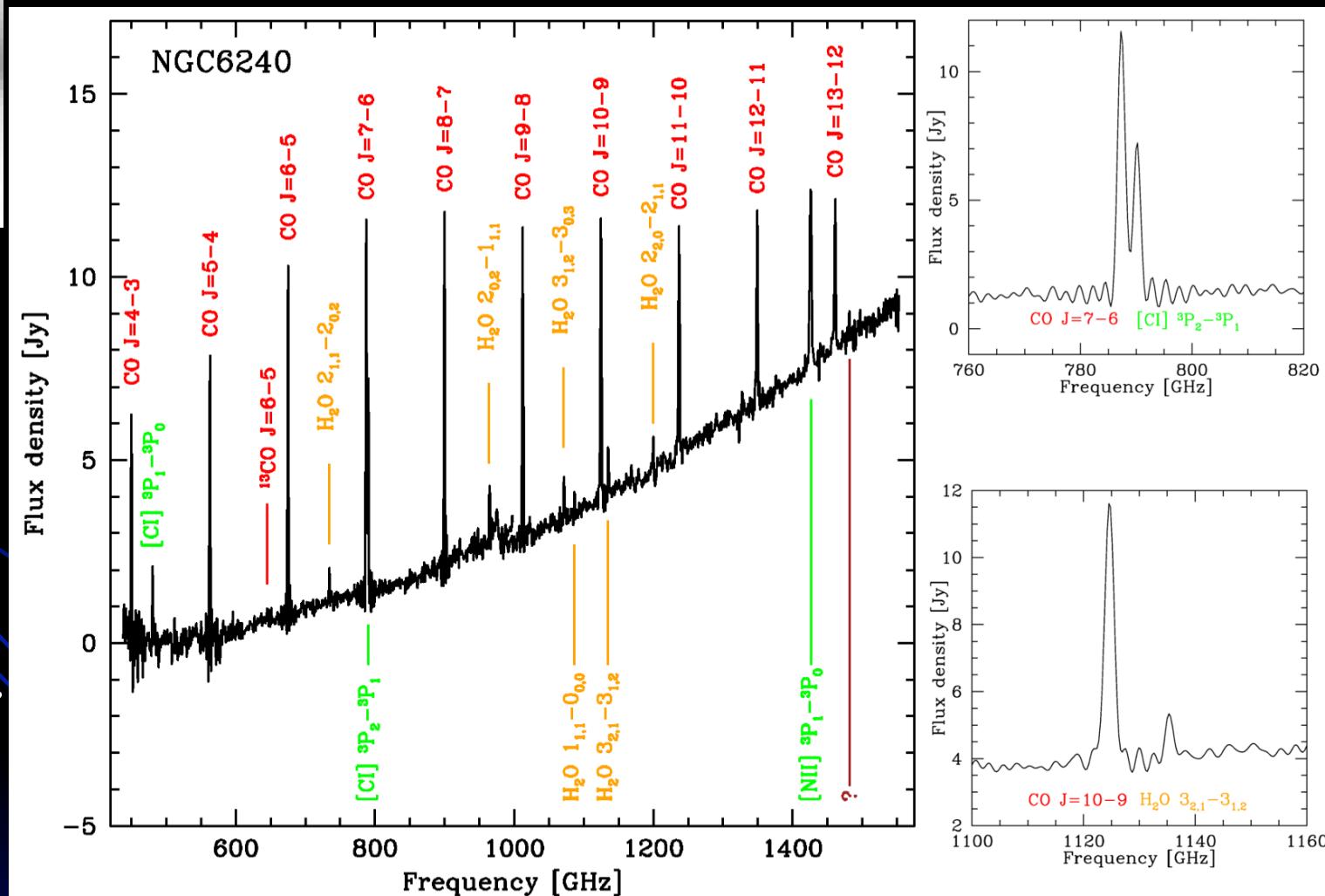
*FTS footprint
Pereira
-Santaella et
al. (2013)*

*Right: FTS
spectra*

*NGC6240
Meijerink et al.
(2013)*

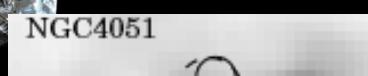
*Mrk231
Van der Werf
et al. (2010)*

Wide spectral range

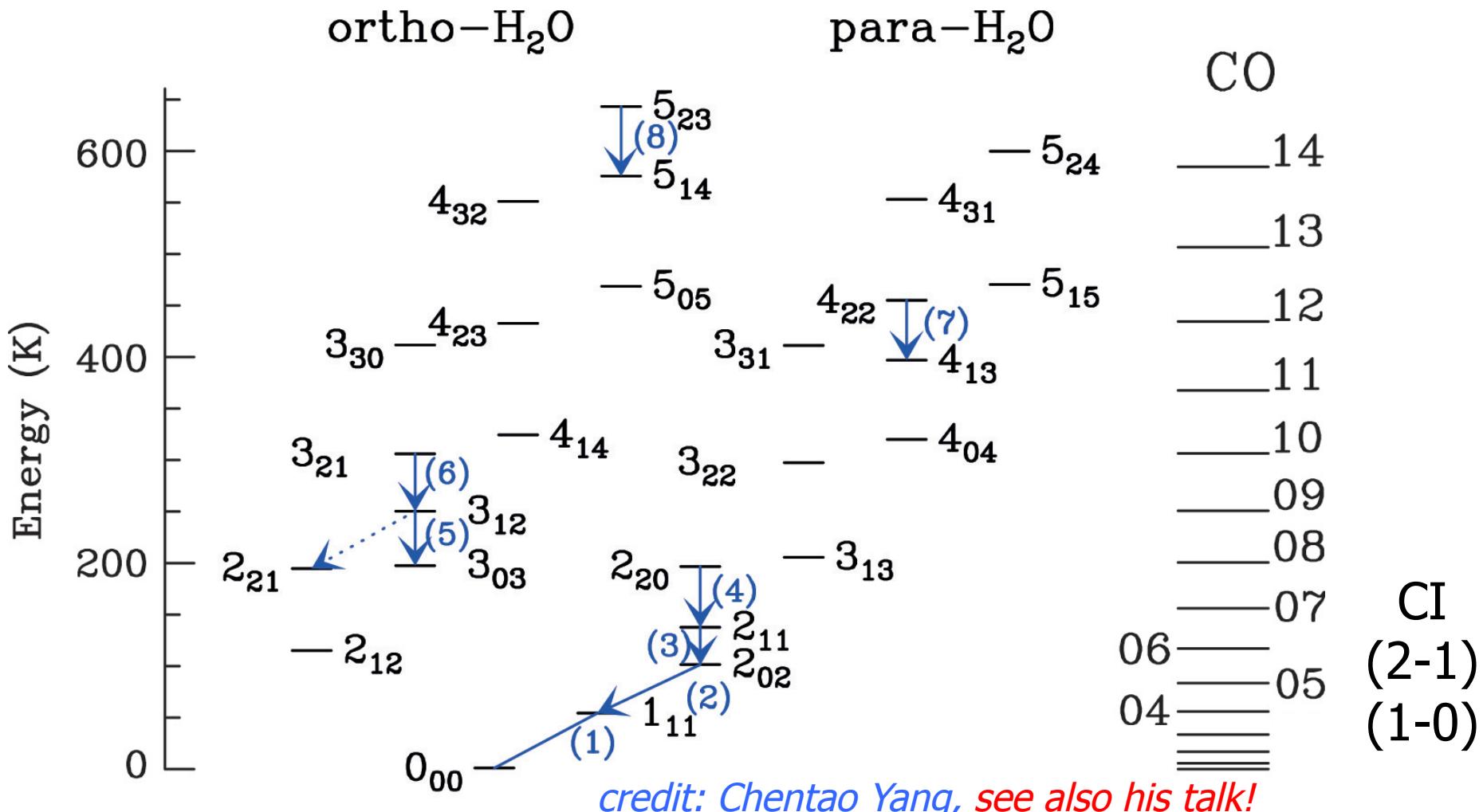




Herschel SPIRE Fourier Transform Spectrometer (FTS)

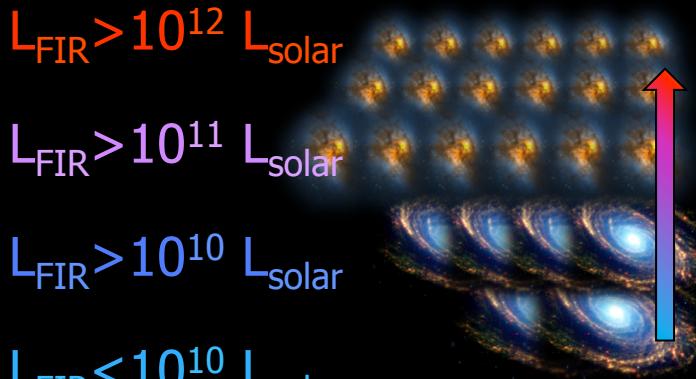


Wide spectral range



A largest FTS local galaxy sample

- ~200 FTS + PACS (phot.) observed galaxies in Herschel Science Archive (**Unique sample in many years!**)
- ~45+ have at least one H₂O detection (Yang et al. 2013 ApJL 771 24; see our poster P06)
- ~90+ have at least one H₂O detection (**This work!** – new calib, doubled sample at the sacrifice of lower S/N, more robust statistics)
 - (U)LIRGs: HerCULES (PI: P. Van der Werf) $L_{\text{FIR}} > 10^{12} L_{\text{solar}}$
 - (U)LIRGs: GOALS (PI: N. Lu) $L_{\text{FIR}} > 10^{11} L_{\text{solar}}$
 - SFGs: VNGS (PI: C. Wilson) $L_{\text{FIR}} > 10^{10} L_{\text{solar}}$
 - SFGs: KINGFISH (PI: J. Smith) $L_{\text{FIR}} > 10^{10} L_{\text{solar}}$
 - SFGs: PI: E. Sturm
 - Dwarf galaxies (PI: S. Madden) $L_{\text{FIR}} < 10^{10} L_{\text{solar}}$
 - ... (*only named half projects, but >90% galaxies*)



A largest FTS local galaxy sample

digging deeper into this unique sample & data

Our Procedures:

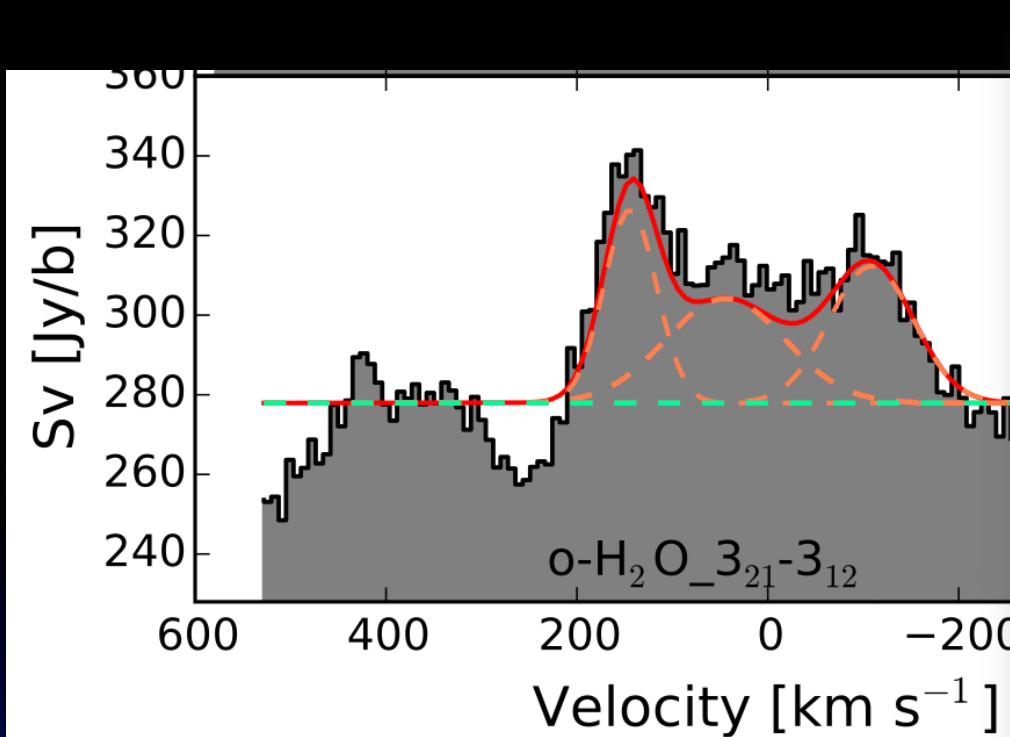
- (1) Comparing FTS H₂O with HiFI
 - *FTS spectral resolution*
- (2) Beam size matched FIR
 - *FTS beam size variation*
- (3) Analyses on marginal detections and stacking data:
 - *Will correlations still be robust?*

Our Goals:

- (1) Statistical correlations between star formation and SPIRE/FTS lines: H₂O, CO, [CI]
- (2) Dense warm gas properties from the rich FTS line inventories

Herschel SPIRE Fourier Transform Spectrometer (FTS)

Spectral resolution

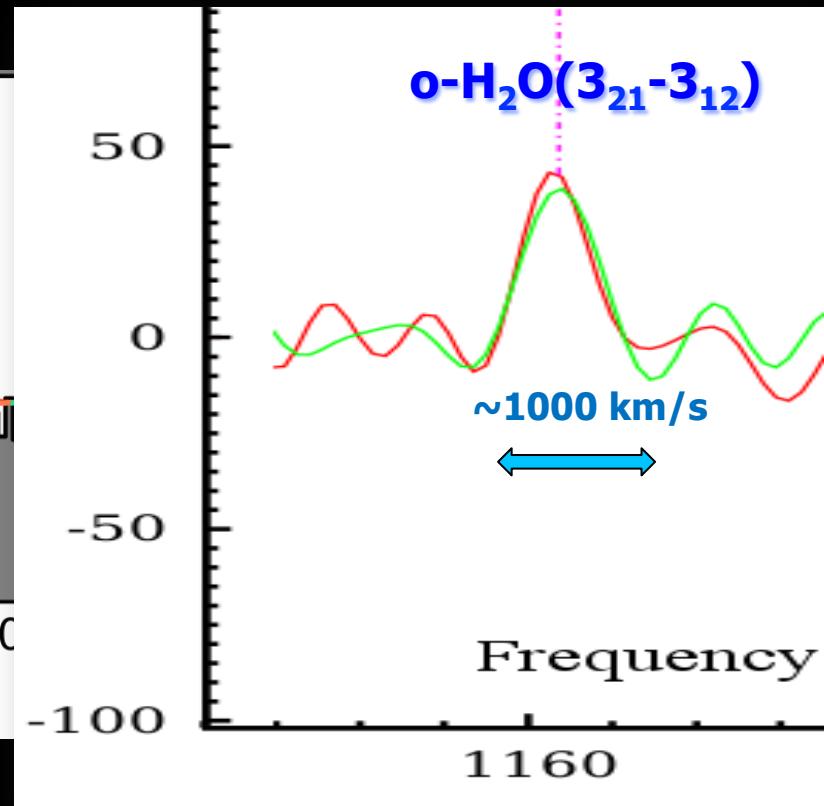


Left:

HIFI data: HEXGAL project PI: R. Güsten

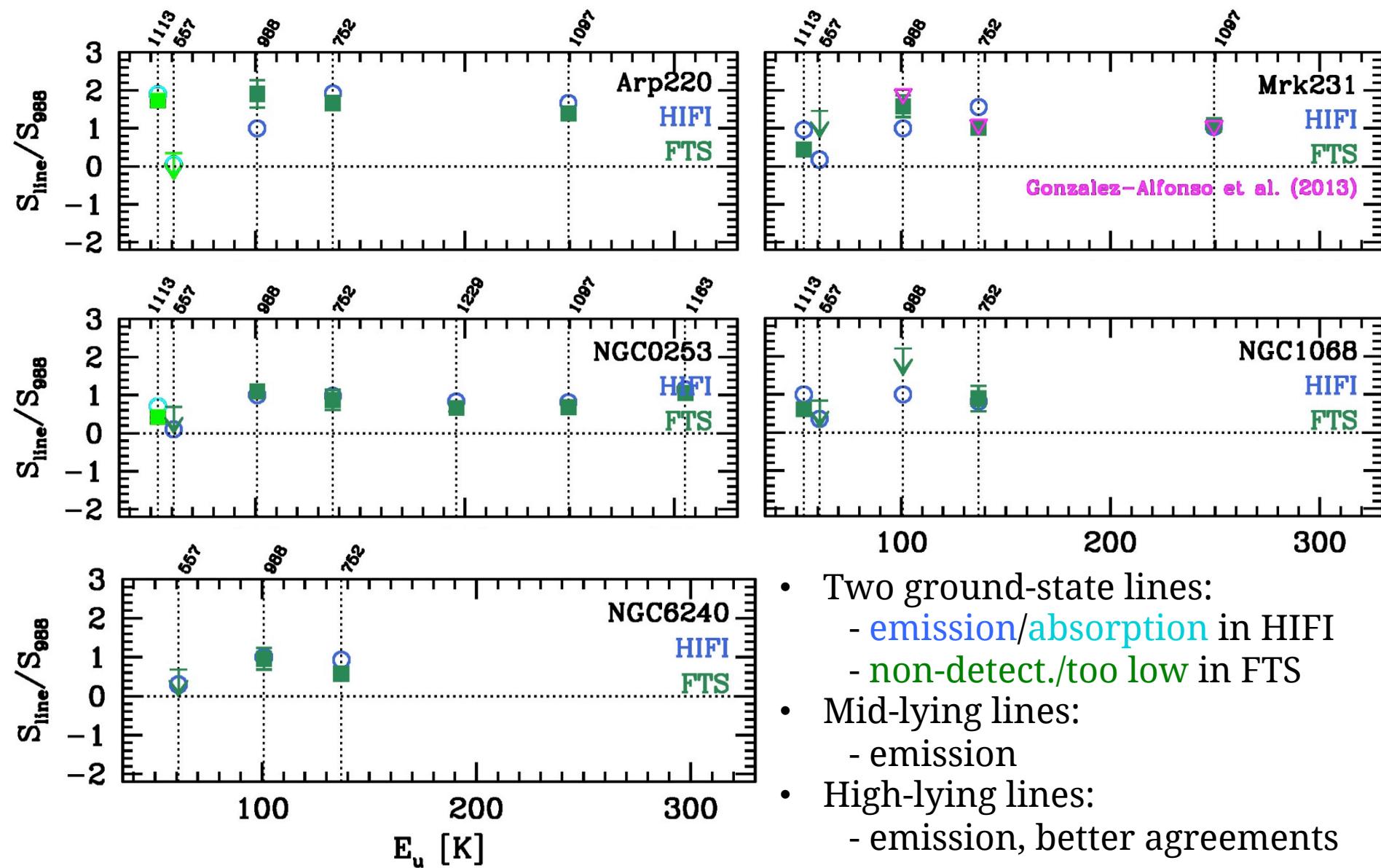
See also Lijie Liu's talk

2016-04-15



Right: FTS data: PI: E. Sturm.

Sample & Data: Comparing FTS H₂O with HIFI

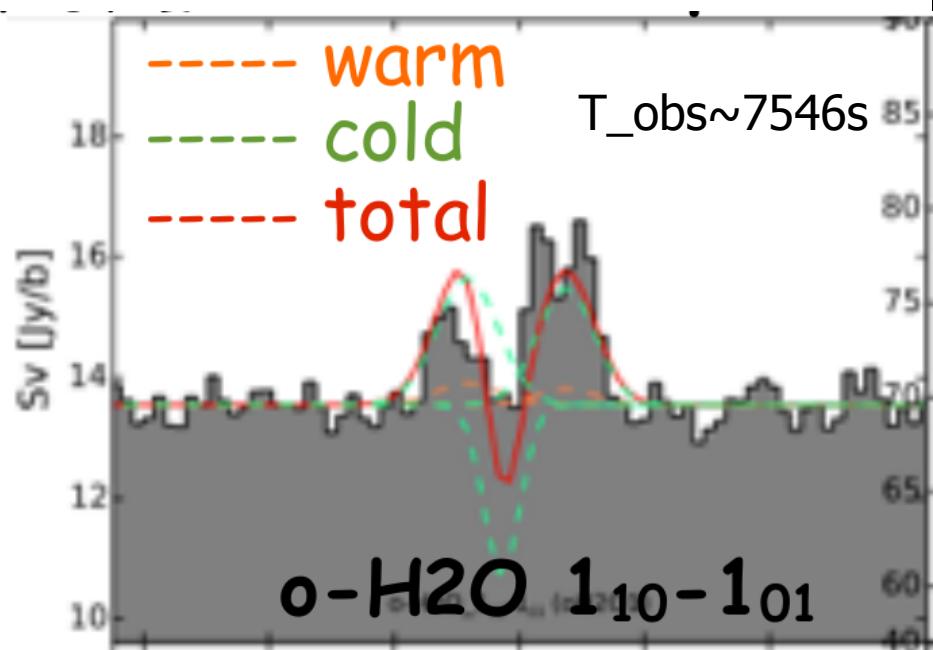


- Two ground-state lines:
 - emission/absorption in HIFI
 - non-detect./too low in FTS
- Mid-lying lines:
 - emission
- High-lying lines:
 - emission, better agreements

Sample & Data: Comparing ortho-H₂O(1₁₀-1₀₁) @557GHz

Left:

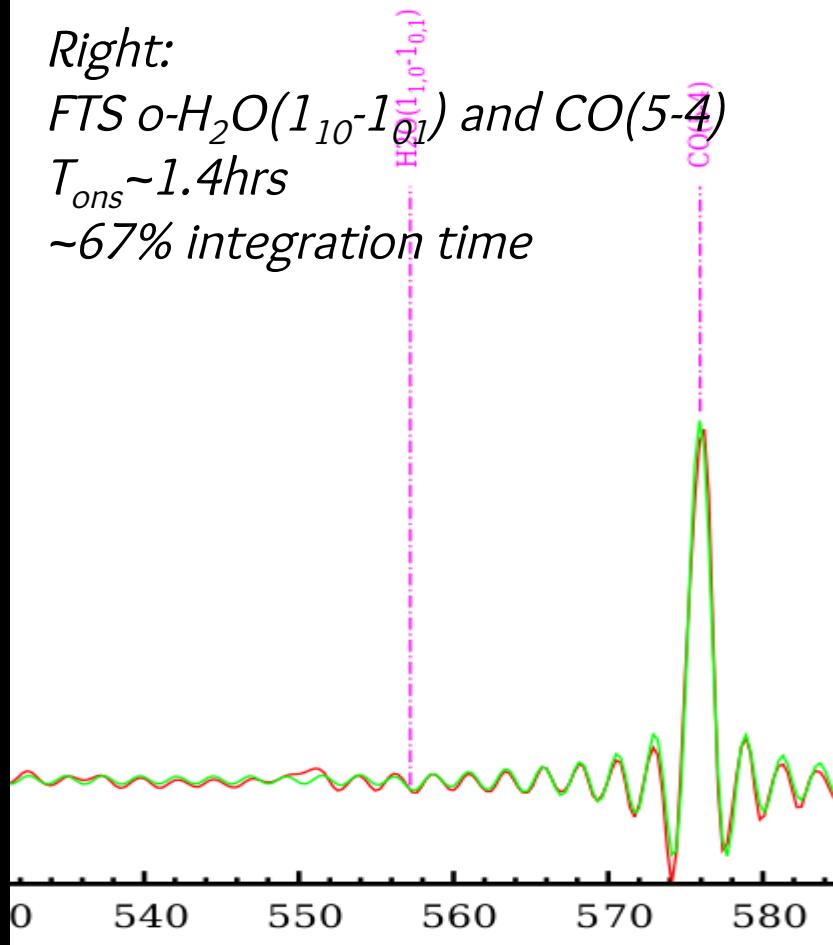
Lijie Liu et al. 2016 (*in prep.*)
M82 HIFI o-H₂O(1₁₀-1₀₁)
 $T_{obs} \sim 2\text{ hrs}$



2016-04-15

Right:

FTS o-H₂O(1₁₀-1₀₁) and CO(5-4)
 $T_{obs} \sim 1.4\text{ hrs}$
~67% integration time



10

Sample & Data: Stacking ortho-H₂O(1₁₀-1₀₁) @557GHz

Stacking of (ultra-) luminous and normal infrared galaxies:

Mrk231

Arp299

NGC3256

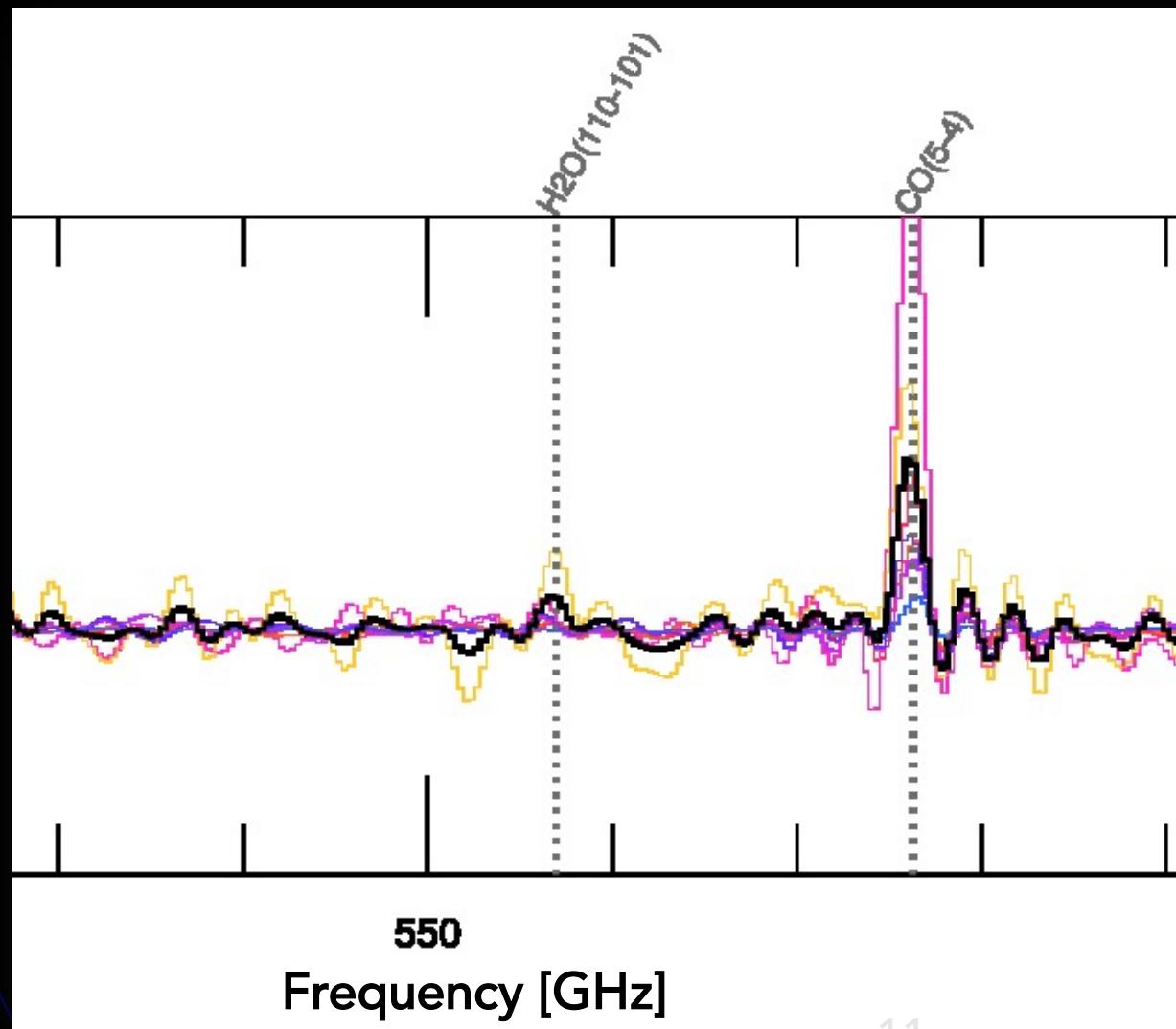
NGC6240

NGC7130

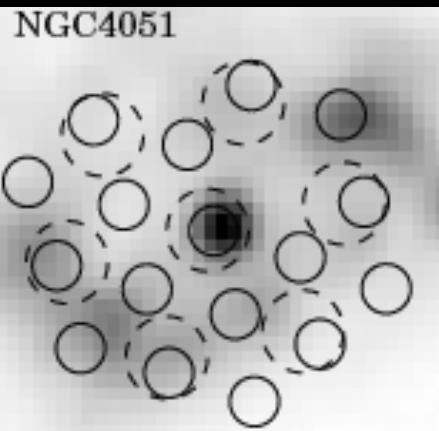
NGC7469

NGC7552

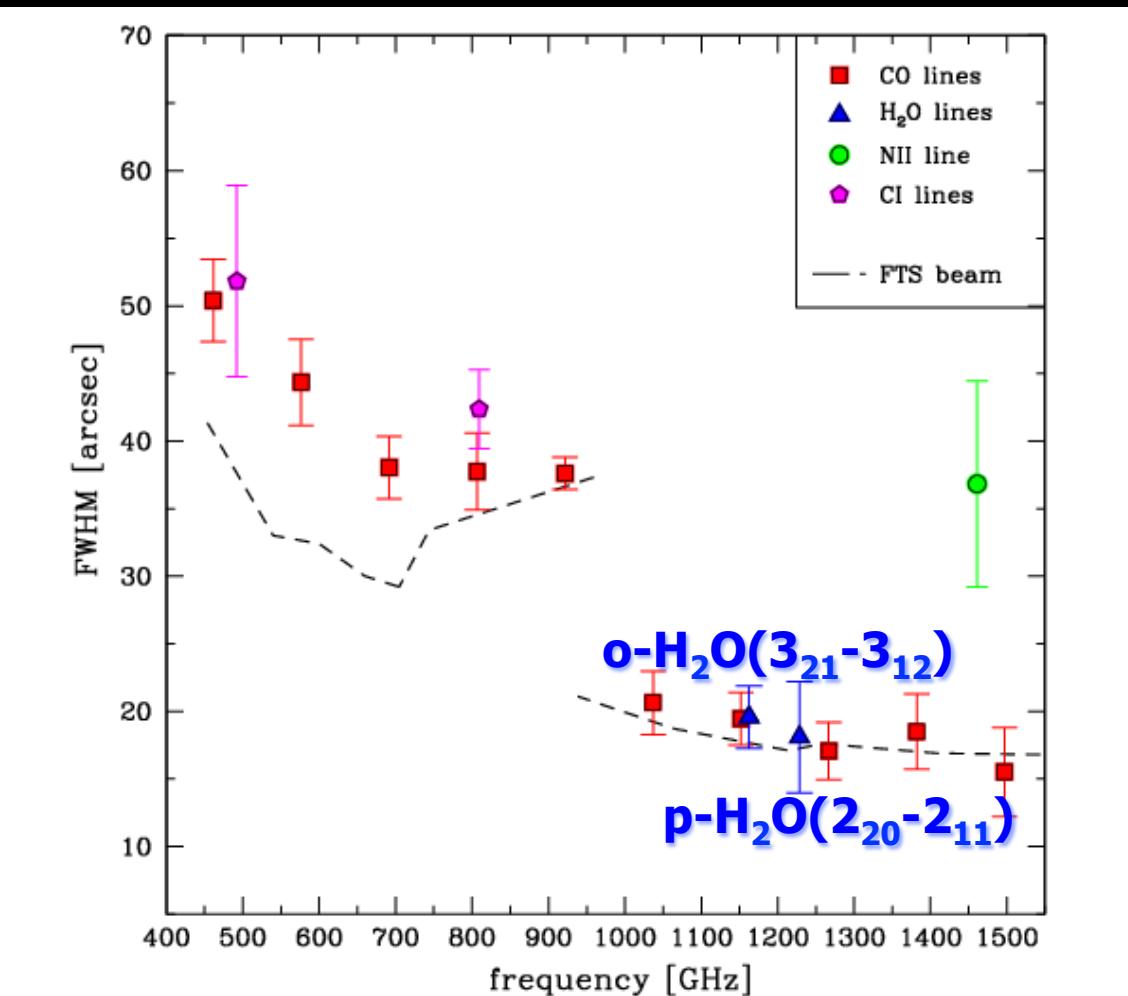
2016-04-15



Sample & Data: Obtaining Far-infrared Luminosity

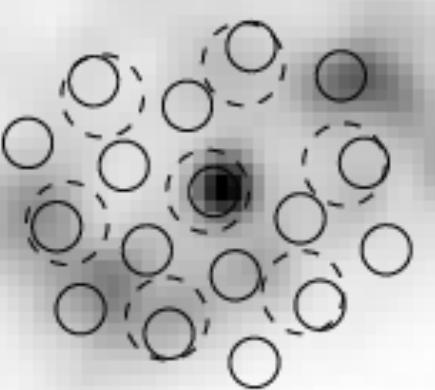


FTS beam size varies as a function of frequency



Sample & Data: Obtaining Far-infrared Luminosity

NGC4051

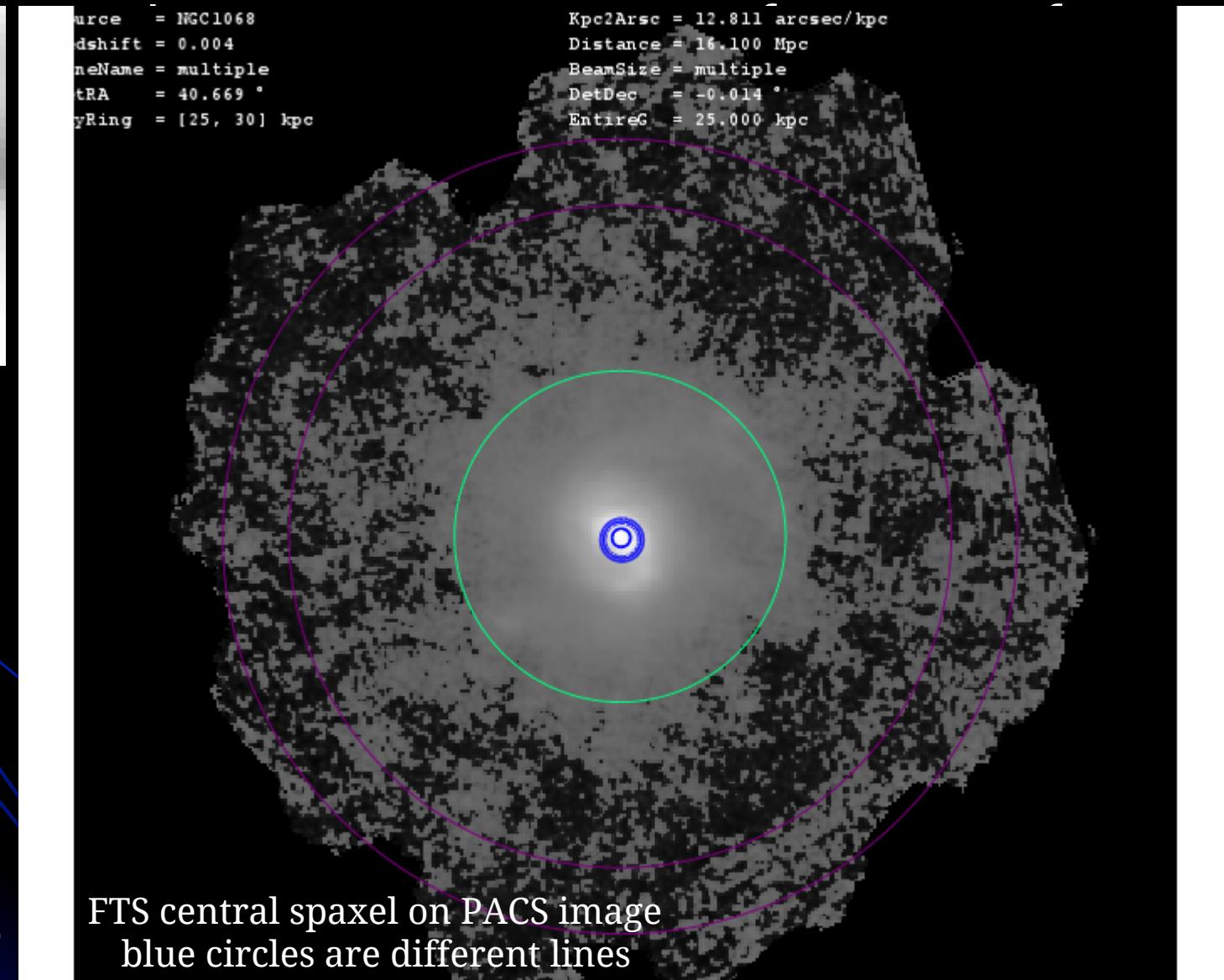


*FTS footprint
Pereira
-Santaella et
al. (2013)*

2016-04-15

```
source = NGC1068
zshift = 0.004
lineName = multiple
tRA    = 40.669 °
skyRing = [25, 30] kpc
```

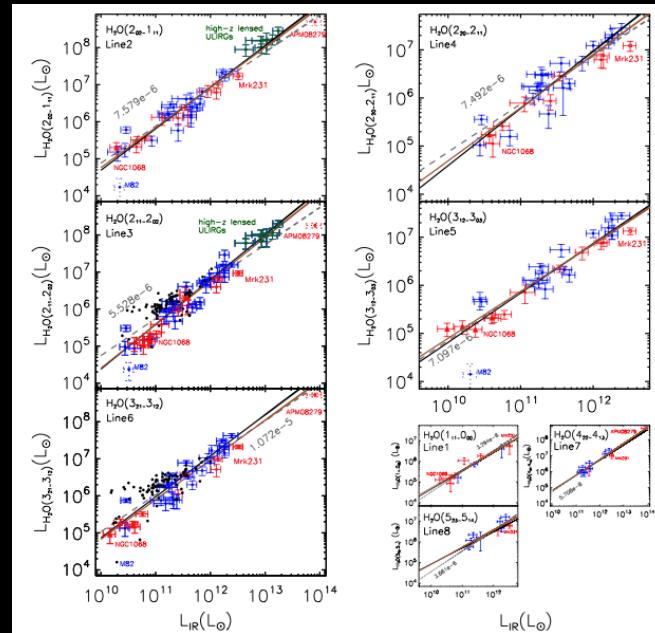
```
Kpc2Arcsec = 12.811 arcsec/kpc
Distance = 16.100 Mpc
BeamSize = multiple
DetDec = -0.014 °
EntireG = 25.000 kpc
```



FTS central spaxel on PACS image
blue circles are different lines

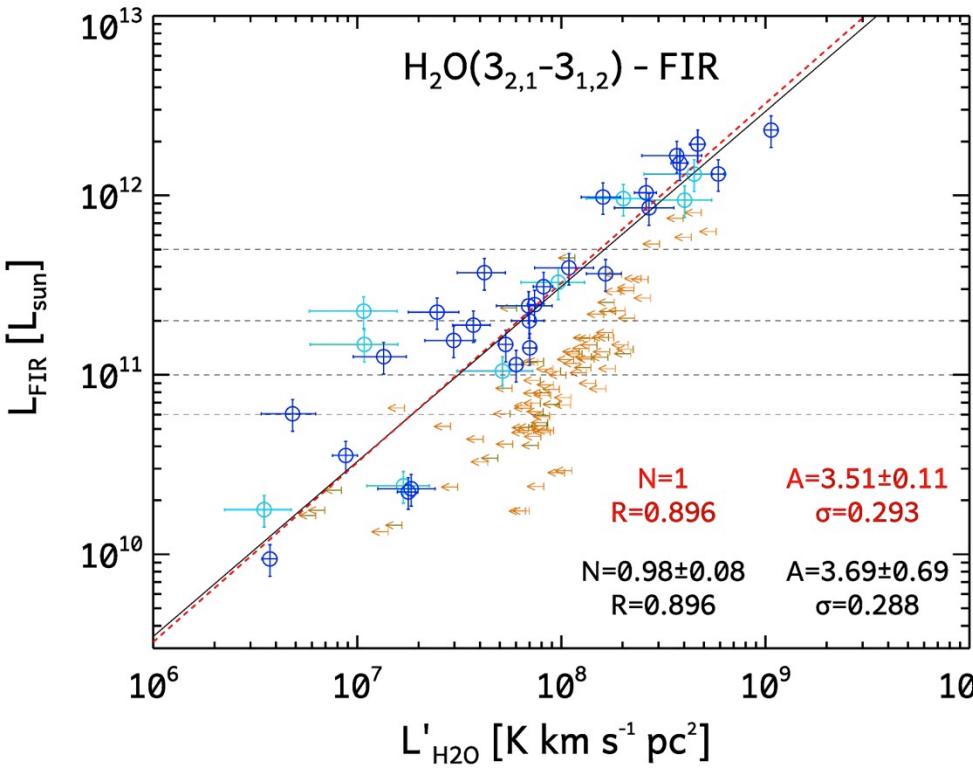
H_2O vs. star formation

- Correlations between H_2O and star formation
 - the importance and uniqueness of Herschel H_2O in galaxies
 - the robustness and reliability of results
- First systematic extragalactic study
 - Yang et al. (2013 ApJL 771 24)
 - see our poster P06
- This work
 - updated calibration
 - also careful beam-matched far-infrared measurements
 - but pushing to lower S/N in order to obtain more robust statistics

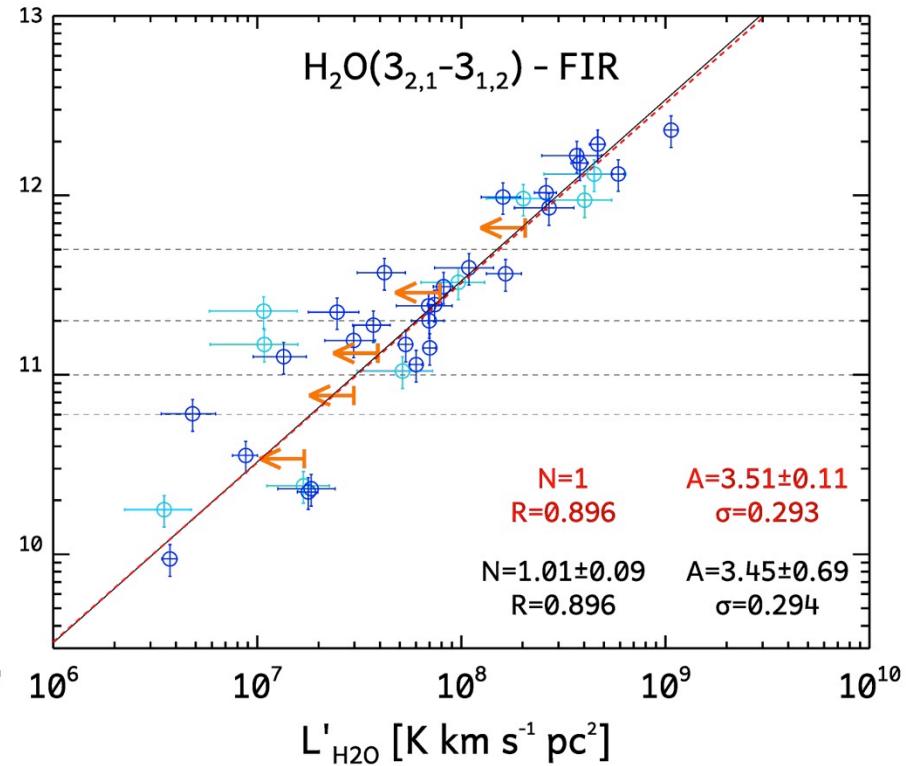


H₂O vs. star formation $J_{upper}=3$

With $2.5 < S/N < 3$ data



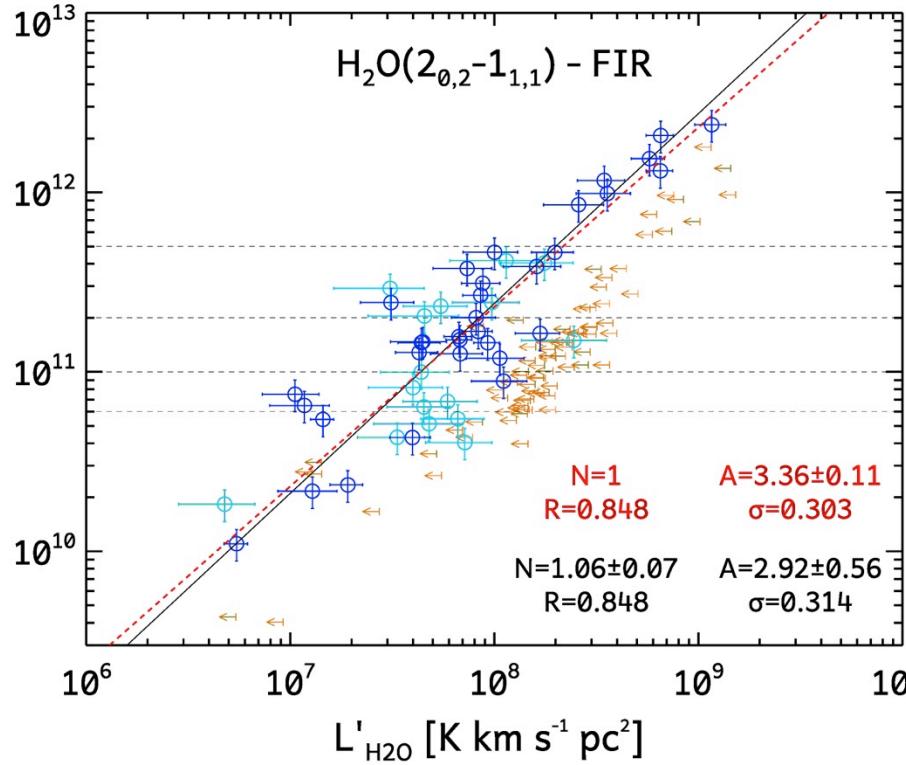
With Stacked data (still upper limits)



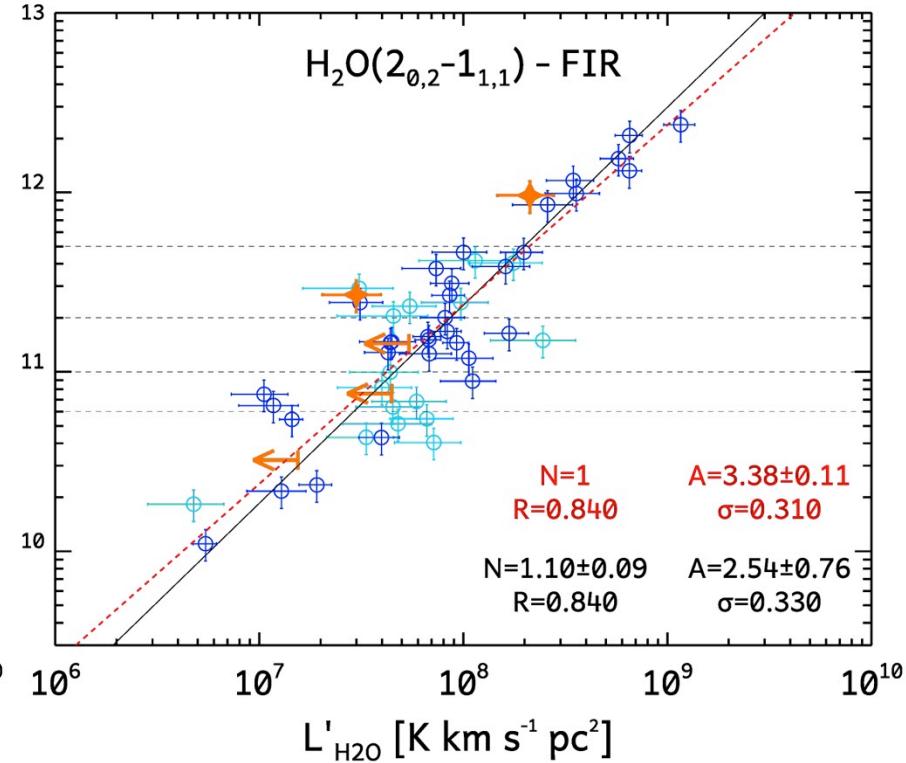
Yang et al. (2013): $N \sim 0.92 \pm 0.09$

H_2O vs. star formation $J_{upper}=2$

With $2.5 < \text{S/N} < 3$ data



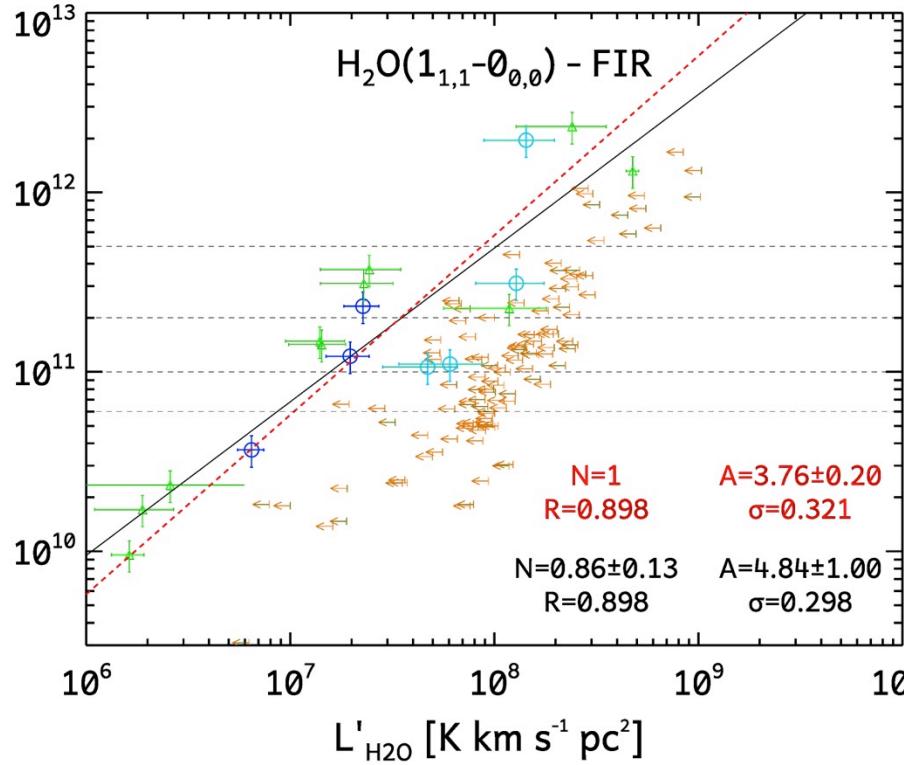
With Stacked data (50% upper limits)



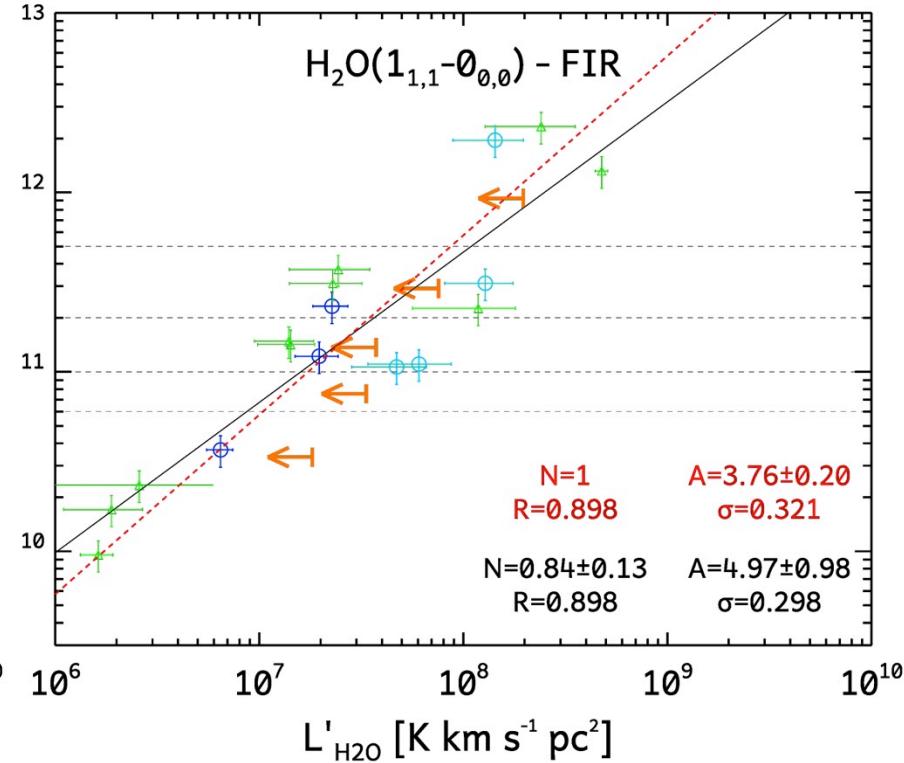
Yang et al. (2013): $N \sim 0.91 \pm 0.05$ (including high redshift galaxies)

H_2O vs. star formation $J_{upper}=1$ @1113GHz

With $2.5 < \text{S/N} < 3$ data



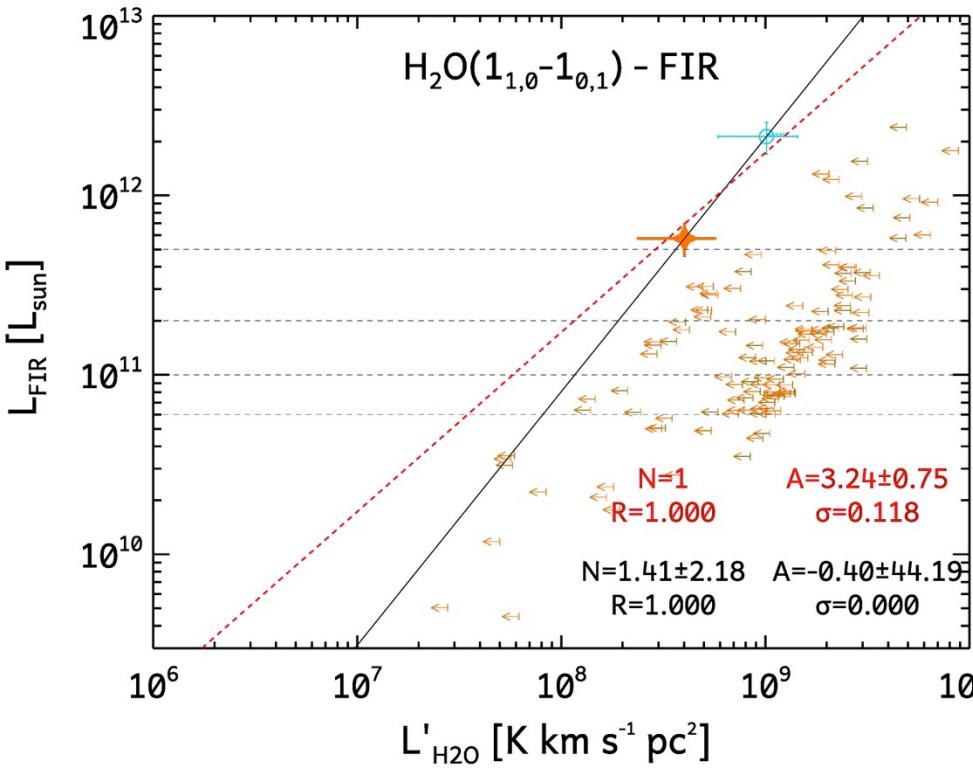
With Stacked data (all upper limits)



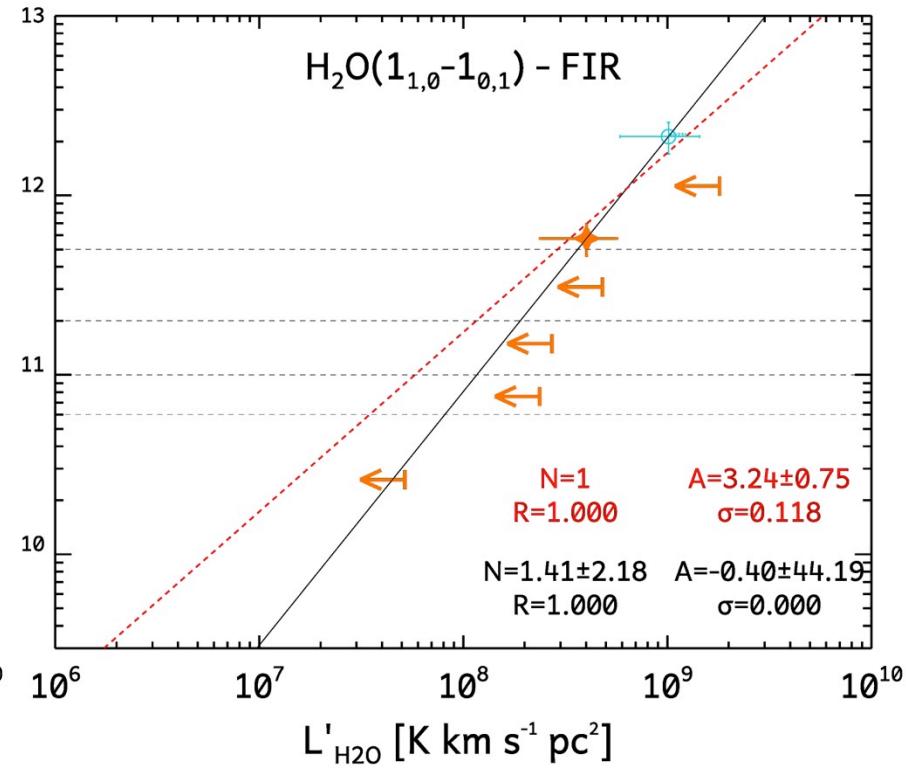
Yang et al. (2013): $N \sim 1.14 \pm 0.17$

H_2O vs. star formation $J_{upper}=1$ @557GHz

With $2.5 < \text{S/N} < 3$ data



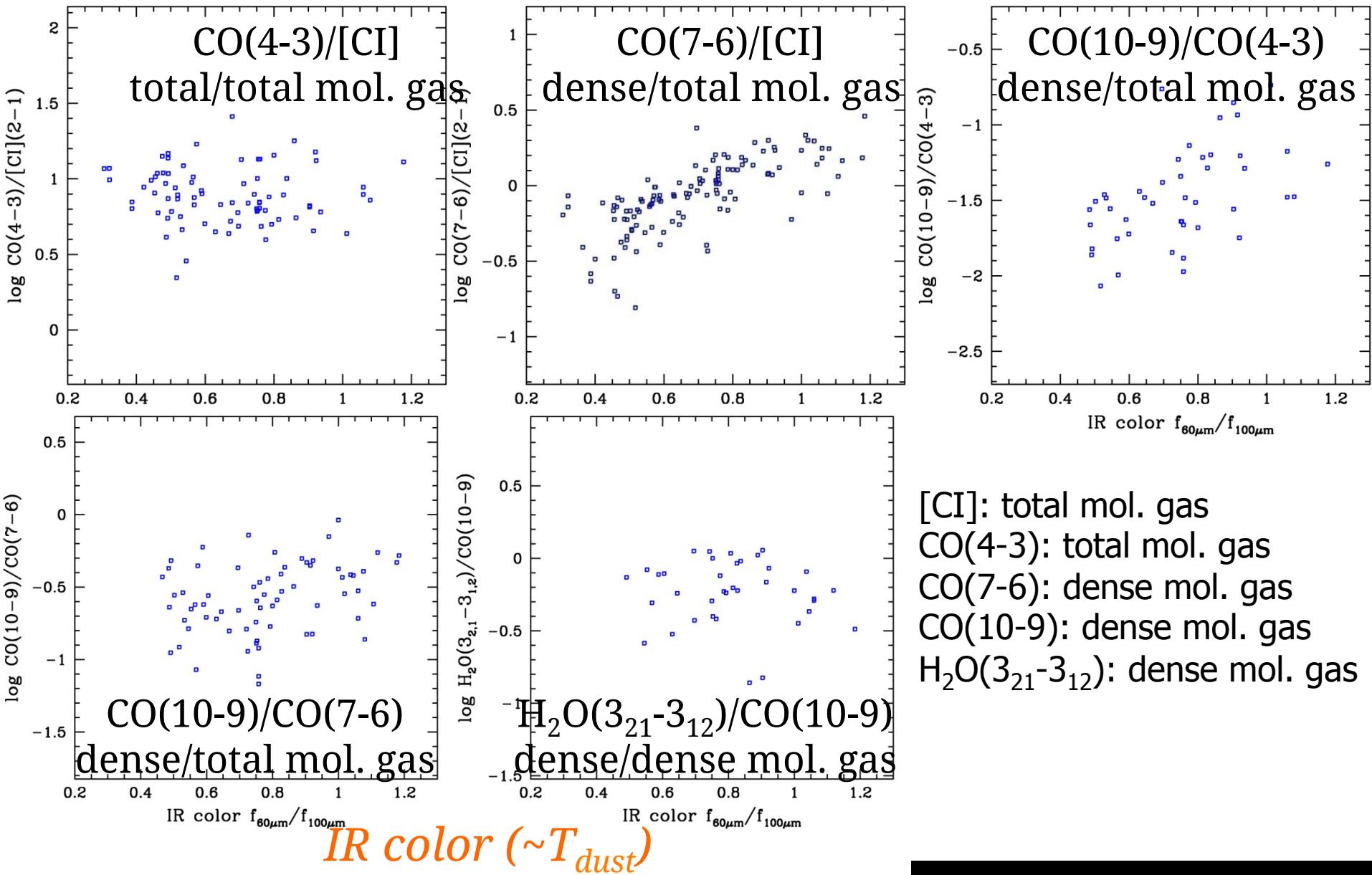
With Stacked data (all upper limits)



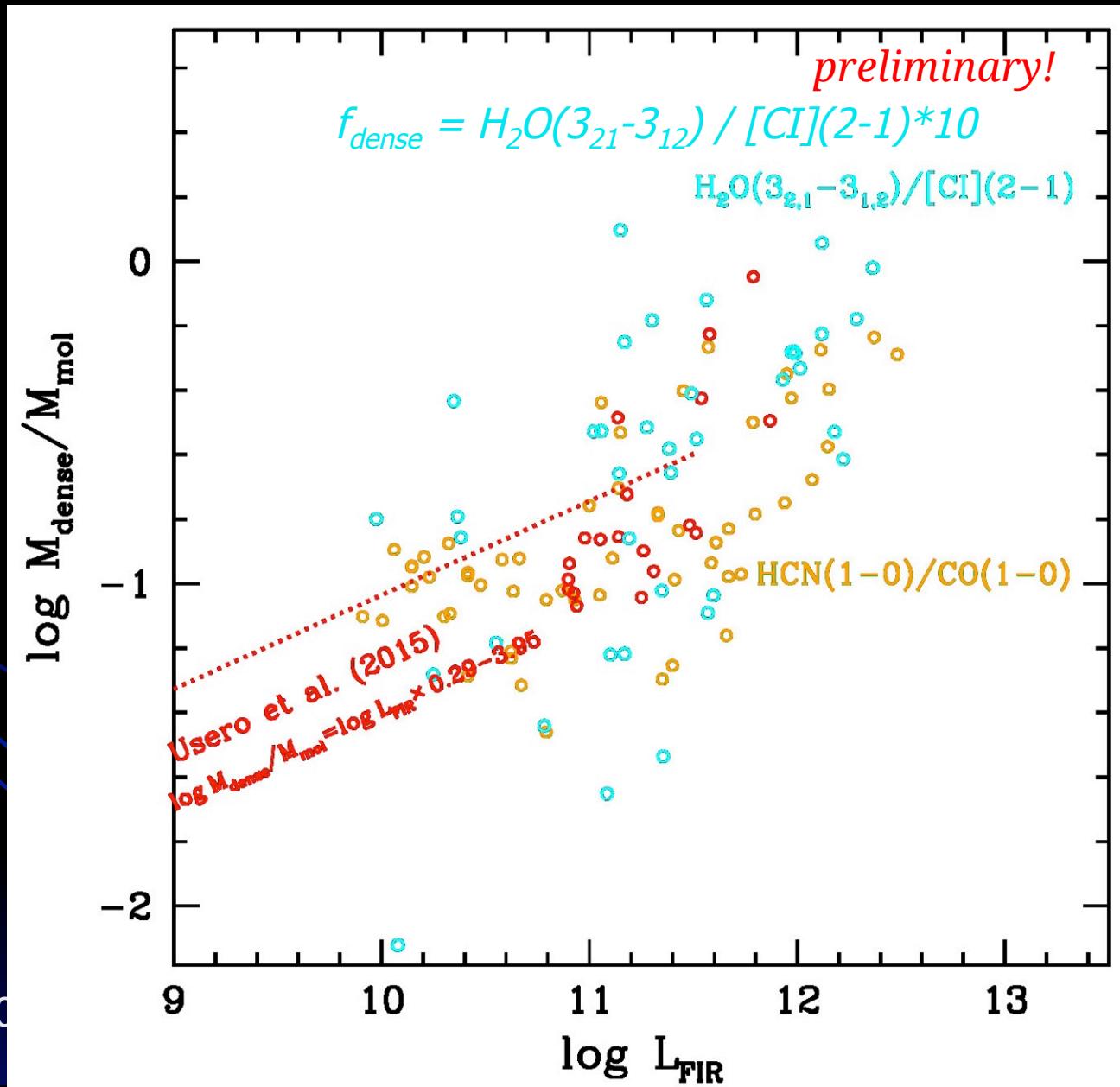
No single $\text{S/N} > 3$ detections in any FTS galaxy spec!
Only one marginal detection: Mrk231 (emission).

Still unsolved!

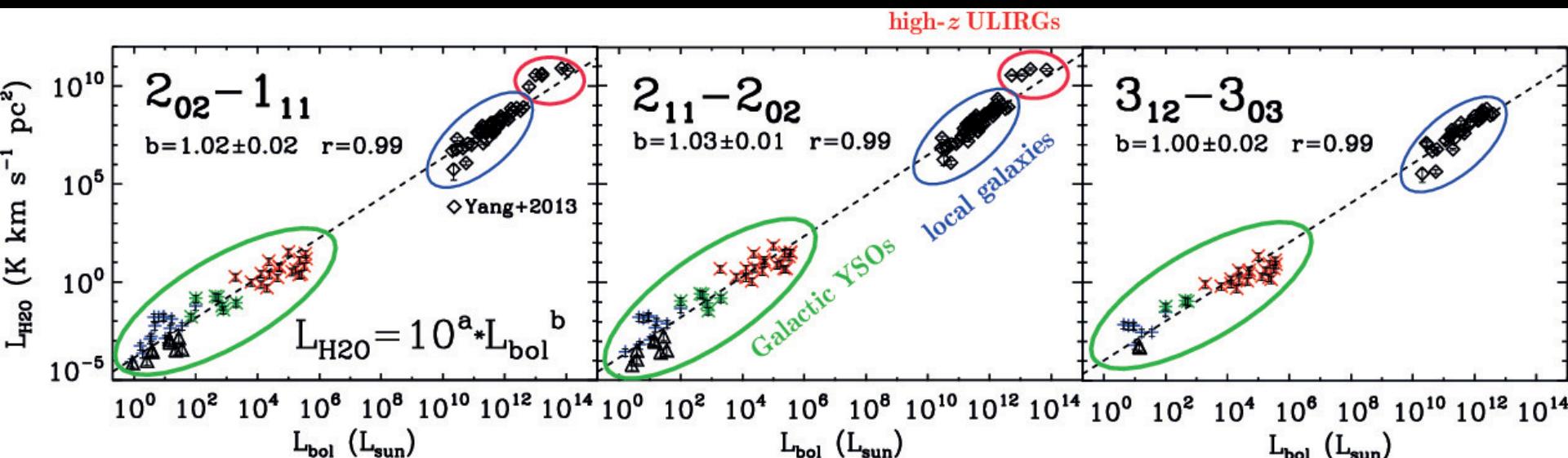
The dense gas probed by FTS lines H_2O , CO and $[CI]$



Converting to the dense gas fraction



Combining Young Stellar Objects and Galaxies



San Jose-Garcia et al. 2016

Summary

➤ *Sample & Data:*

- **Unique sample & data:** ~90+ local galaxies with at least one H₂O detection in Herschel SPIRE FTS archive. Carefully measured far-infrared.
- **Deeper & stronger statistics:** doubled the sample at the sacrifice of S/N. Adopted stacking to provide deepest FTS upper limits.

➤ *Highlights:*

- Statistically robust linear correlations between H₂O and star formation
- FTS H₂O/[CI] as probes of dense star-forming gas
- Benchmark for high redshift H₂O studies

THANK YOU!

D. Liu & Y. Gao & C. Yang
Purple Mountain Observatory
dzliu@pmo.ac.cn
[& yugao@pmo.ac.cn](mailto:&yugao@pmo.ac.cn)

2016-04-15 ESA/ESTEC Water in the Universe

