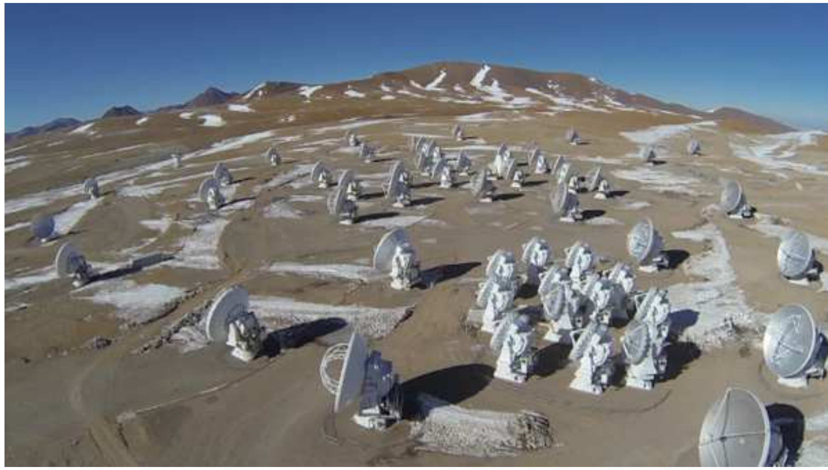

IRAM Plateau de Bure 6 → 12 x 15m



ALMA

**Detections of hydrides in high z sources, current analysis, and diagnostics**

*Alain Omont (IAP, CNRS & UPMC)*

# OUTLINE

## ➢ Specificities of high-z observations of hydrides

**Better atmospheric windows, many ULIRGs, lensing, external absorption systems**

## ➢ Current analysis of detections

- $H_2O$ and associated molecules
- $CH^+$, HF and others
- External molecular absorption systems

## ➢ Diagnostics

- Line excitation (IR, collisions ($H_2$, $e^-$), shocks, XDR
- N(H2), $L_{IR}$ ,etc.
- Chemistry, depletion
- Isotopic ratio
- Galaxy structure: nucleus, disk, (halo)
- Outflows (inflows)

## Specificities of high-z observations of hydrides

**The large distance dimming may be partially compensated by several factors**

- **Strong submm lines are redshifted in the millimeter range where they may be observed in very good conditions**
- **The strongest sources, Ultra-Luminous InfraRed Galaxies (ULIRGs), are much more numerous than locally**
- **Gravitational lensing may increase the sensitivity by an order of magnitude, and wide-field submm/mm surveys have multiplied the number of strongly lensed high-z ULIRGs**

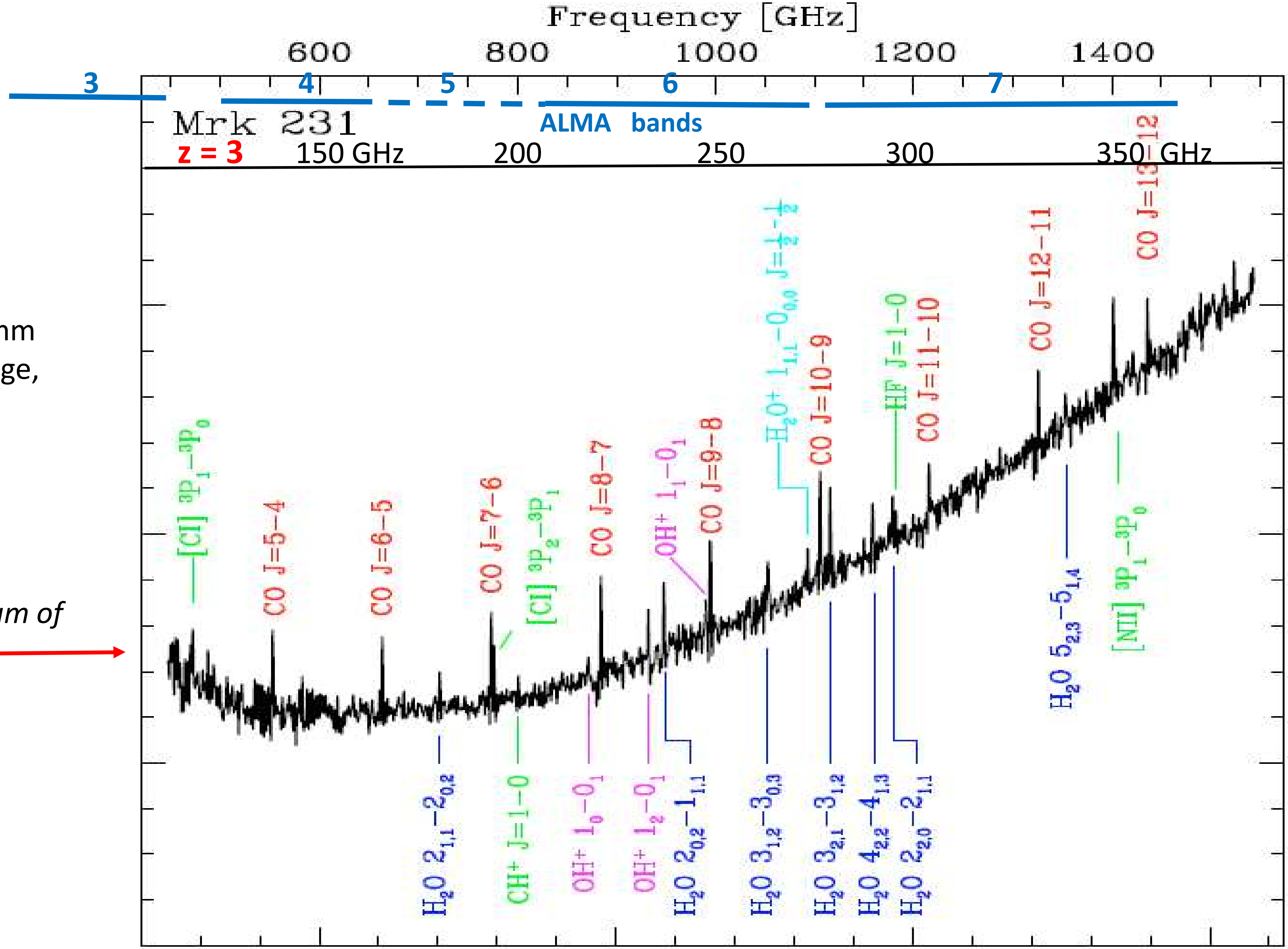
***Altogether ALMA allows studies of z~2-5 ULIRGs with a sensitivity comparable to that of Herschel for local ULIRGs***

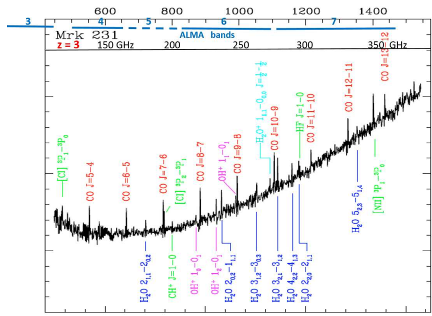
***In addition, the few known high-z Molecular Absorbers present the richest collection of high-z hydrides (in spiral galaxy disks) → S. Muller's talk***

High redshift z ~(2-4) brings strong 'SPIRE' hydride submm lines into the millimeter range, and many in good windows

$H_2O$, $H_2O^+$, $OH^+$, $CH^+$, HF
→ $ArH^+$, $H_3O^+$, etc.

*See e.g. the submm spectrum of Mrk 231 redshifted to z=3*






# High-z ULIRGs

High-z observations of hydride submm lines focus of course on the most powerful emitters

They are also the most luminous galaxies emitting most of their energy in the far-IR, with $L_{IR}$ ~ a few $10^{12}$ - $2 \times 10^{13}$ Lo

Most are found in submm/mm surveys (SCUBA, Herschel, SPT, etc.) and are also named SMGs or DDSs (see e.g. Blain 2016)

They are mostly powered by the most powerful starbursts known (with a possible significant AGN contribution in a minority of them), with a star formation rate (~200-2000 Mo/yr) well above the galaxy 'Main Sequence'.

Although they are much less numerous than typical high-z galaxies (<~1%), several $10^5$ are currently known

Most of their FIR continuum and submm line emission comes from their compact cores (r <~1 kpc)

Many of them should result from major mergers as local ULIRGs

# Strongly lensed SMGs

**A very small minority of high-z SMGs are strongly lensed**
**Magnification factors ~3 to 10 or more**

**Most lens deflectors are massive early galaxies at z~0.2-1**
**But there is a significant fraction of galaxy groups and a very few galaxy clusters**

**Hesrchel and SPT surveys have multiplied the number of known lenses by two orders of magnitude**
**From a few (FIRAS10214, Cloverleaf, APM0827, Eyelash, etc.) to several hundreds**

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But the redhift determination of the background high-z galaxy needs a sensitive broad-band CO observation (better by ALMA).
Even the redshift determination of the deflector proves difficult in a few cases (when >~1) .

The magnification increases the sensitivity and the angular resolution
However, the interpretation of the (ALMA, NOEMA, SMA, etc.) is not straightforward,
but needs elaborate modeling (e.g. Bussmann et al. 2013)
Differential lensing may distort line ratios and profiles

## Altogether ALMA allows studies of z~2-5 ULIRGs with a sensitivity comparable to that of Herschel for local ULIRGs

### Similar class of objects

- Compact cores + extended component
- Similar (core) Far-IR luminosity (or SFR) surface density
- Similar submm hydrid lines both emission and absorption ; and similar line ratios

→ Similar excitation processes and diagnostics

- Possible strong buried AGN in a minority of them

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### But significant differences

- Stronger FIR (up to 2 x$10^{13}$Lo) and line luminosities
- Closer to starburst instability
- More extended core(s)
- Possibly more various structures and less major mergers
- Probably more strong outflows (see E. Falgarone's talk)

# Current analysis of detections

- $H_2O$ and associated molecules ($H_2O^+$, $OH^+$, OH, $H_2{}^{18}O$)
- $CH^+$ *(see E. Falgarone's talk),* HF, $NH_3$ and others
- External molecular absorption systems *(see S. Muller's talk)*

**Richest sample of detections of high-z hydride lines**
**$H_2O$, $H_2O^+$, $OH^+$, OH, $H_3O^+$, $CH^+$, CH, HF, $ArH^+$, $H_2Cl^+$, $NH_2$, $NH_3$, etc.**

# $H_2O$ and associated molecules ($H_2O^+$, $OH^+$, $H_2{}^{18}O$)

## In a sample of 16 H-ATLAS strongly lensed galaxies

***On behalf of Chentao Yang and the H-ATLAS and IRAM teams***

***Omont et al. 2011, 2013, Yang et al. 2016 and in prep.***

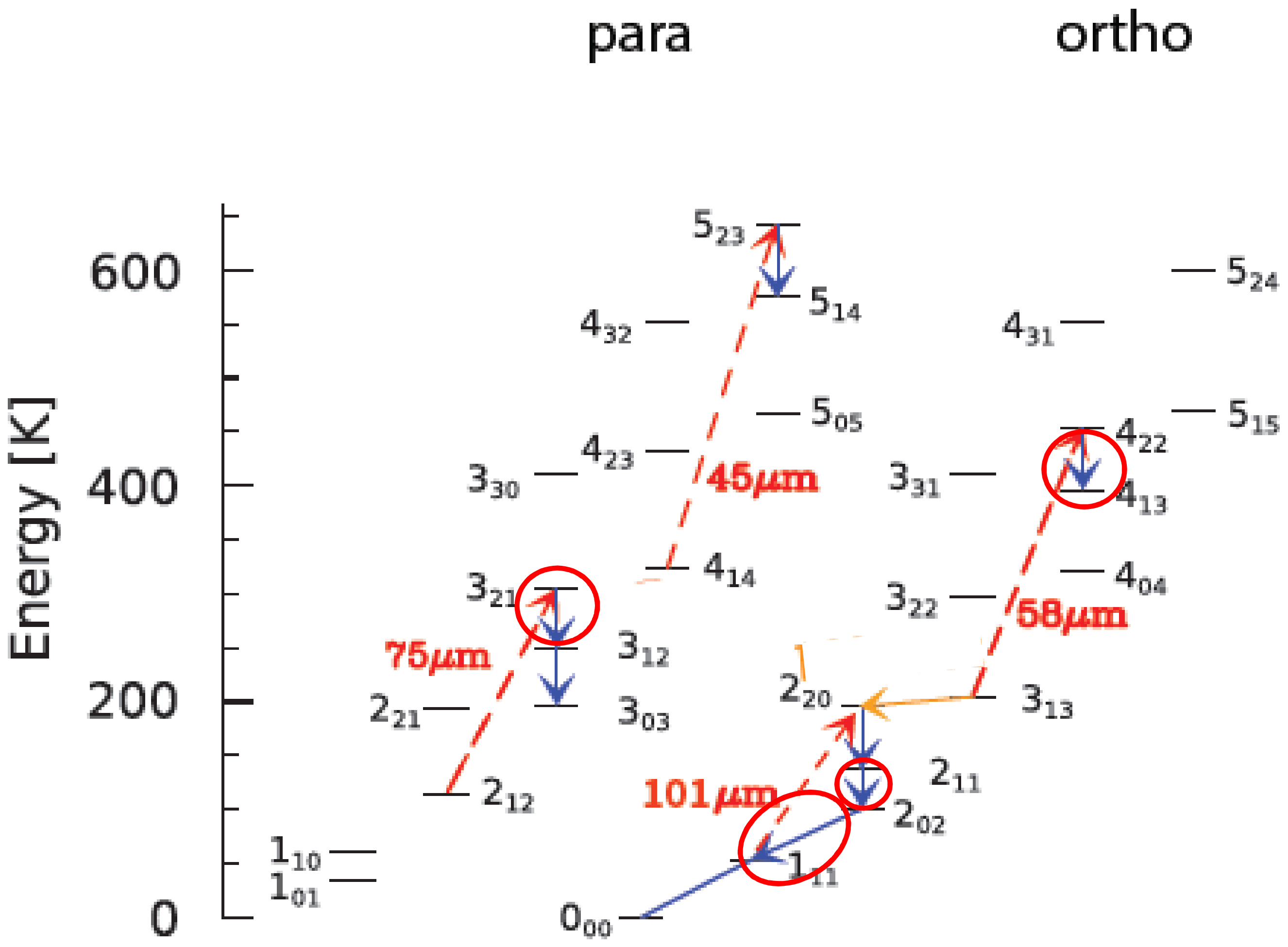
## See also:

**- Early (in FIRAS 10214, Cloverleaf, APM 0827) and other $H_2O$ detections in Herschel or SPT lensed sources** *(Casoli et al. 1994, Lis et al. 2011; van der Werf et al. 2011; Bradford et al. 2011; Combes et al.2012; Lupu et al. 2012; Bothwell et al. 2013; Vieira et al. 2013; Weiß et al. 2013; Rawle et al. 2014, etc.)*

**- Detection of $H_2O$, $H_2O^+$ , OH, $OH^+$, $NH_3$ in HFLS3 at z=6.34** *(Riechers et al. 2013)*

**- Detection of $H_2O$ megamasers at z = 0.66 and 2.64 by** *Barvainis & Antonucci (2005)* **and** *Impellizzeri et al. (2008),* **while further searches have failed since then** *(McKean et al. 2011),* **including in Herschel lensed sources.**

# $H_2O$ rotational levels




Submm emission lines detected
- by SPIRE in local ULIRGS →
- by NOEMA at high z ⊙→

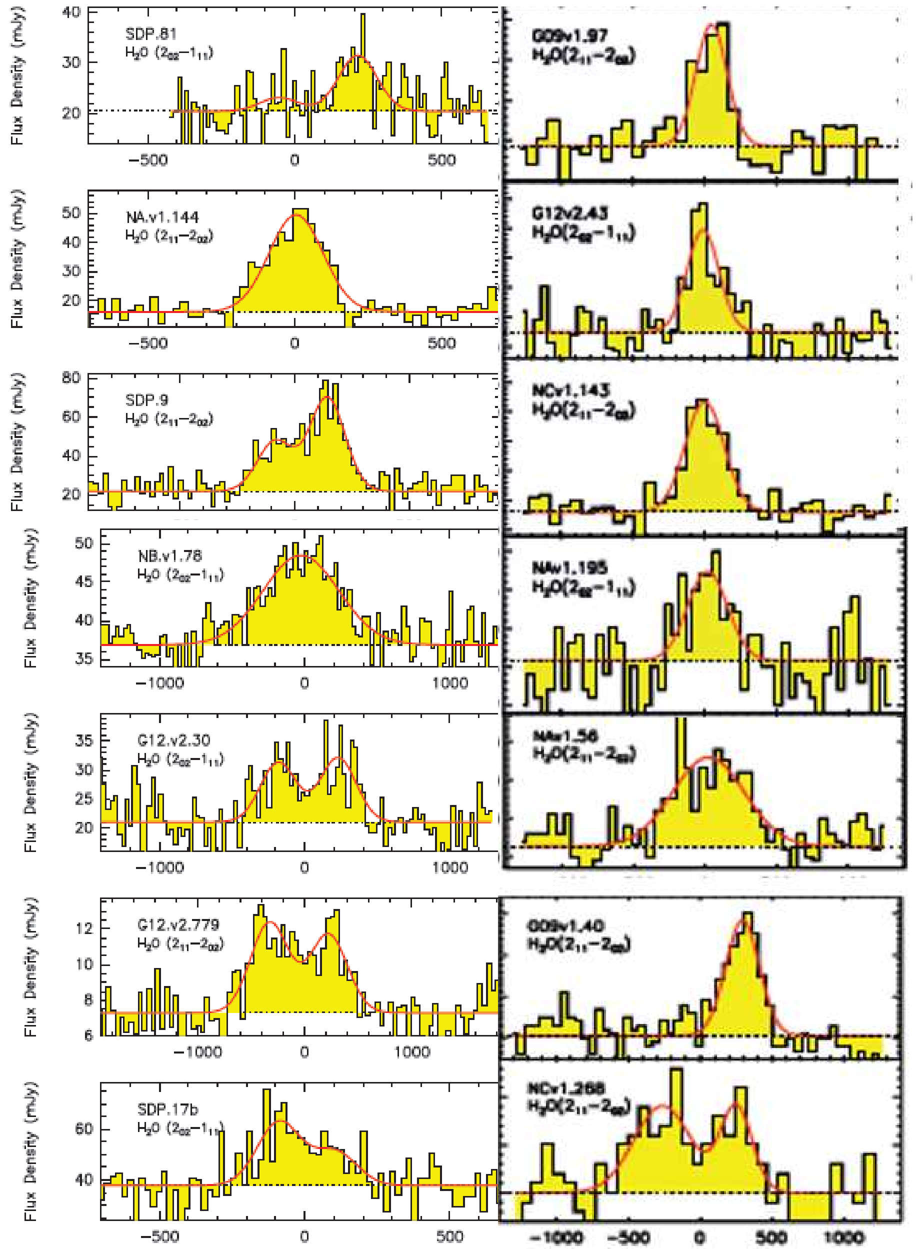
Main far-IR excitation lines - - - >

# $H_2O$ in H-ATLAS lensed sources

→ detected in all observed (16) lenses
with PdBI (NOEMA)
(J=2 ortho lines, $E_{up}$ = 100-130 K)

→ $H_2O$ is strong in all high-z ULIRGs

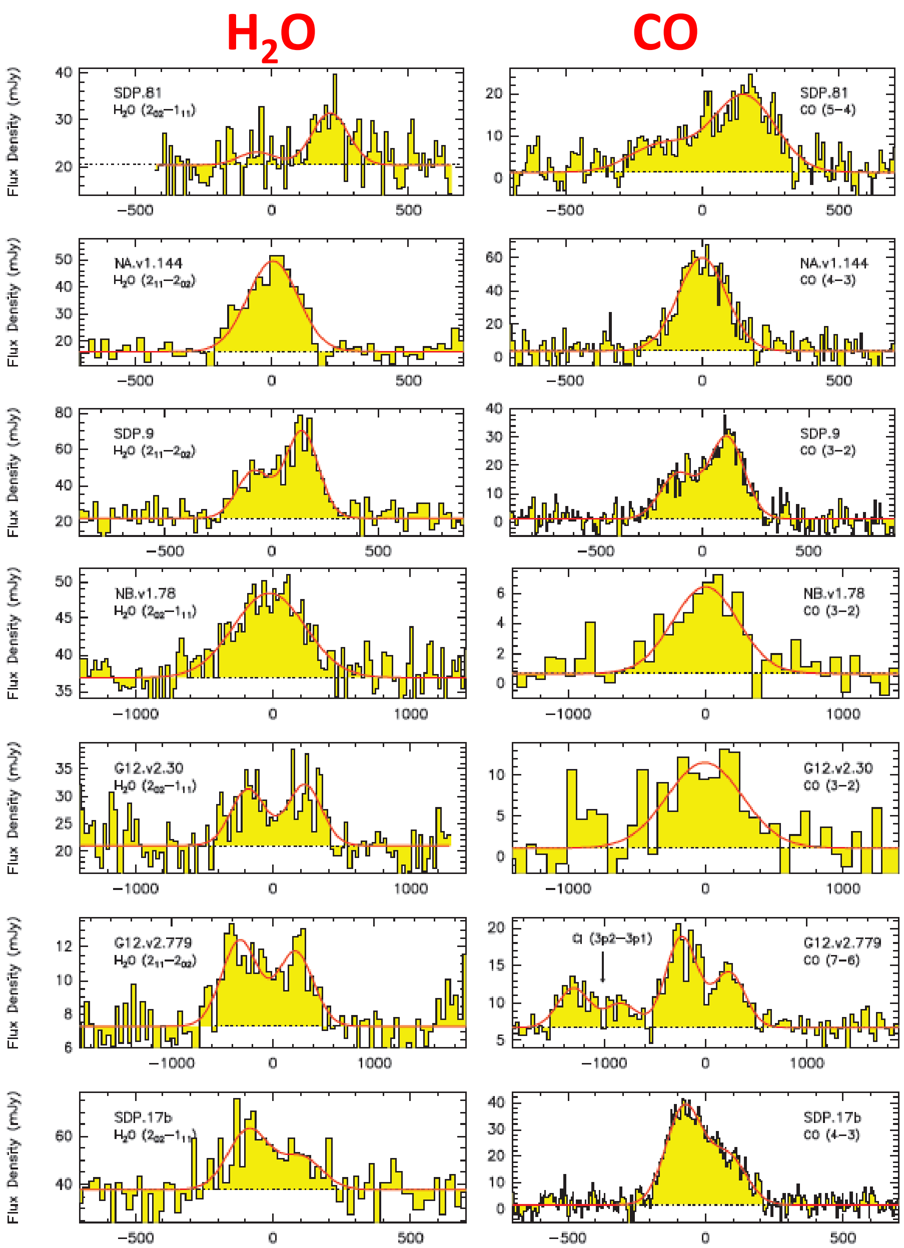
→ strongest molecular lines besides CO



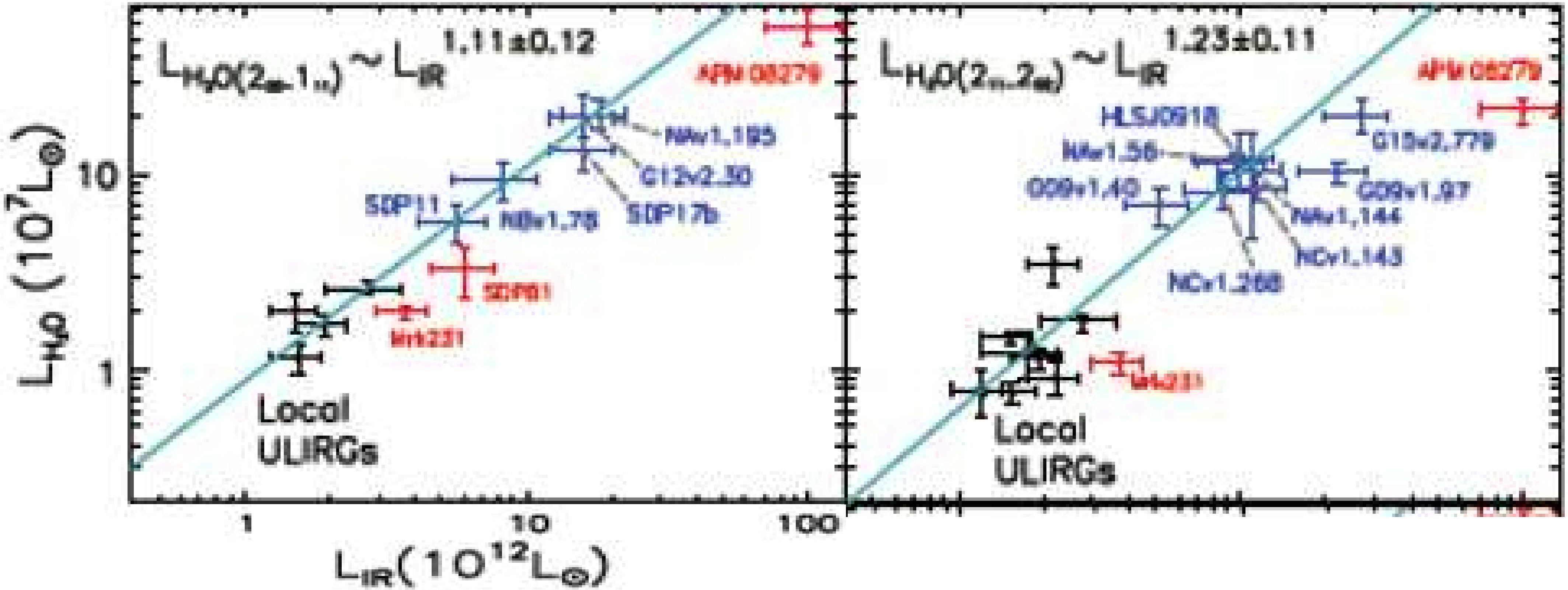
## $H_2O$ in H-ATLAS lensed sources

- ➢ detected in all observed (16) lenses with PdBI
- → $H_2O$ is strong in all high-z ULIRGs
- → strongest molecular lines besides CO

- ➢ Striking similarities of $H_2O$ and CO line profiles
- → Same region of emission
- → No strong differential lensing



## Good correlation with $L_{IR}$




**Good correlation of $L_{H2O}$ with $L_{IR}$, almost linear**

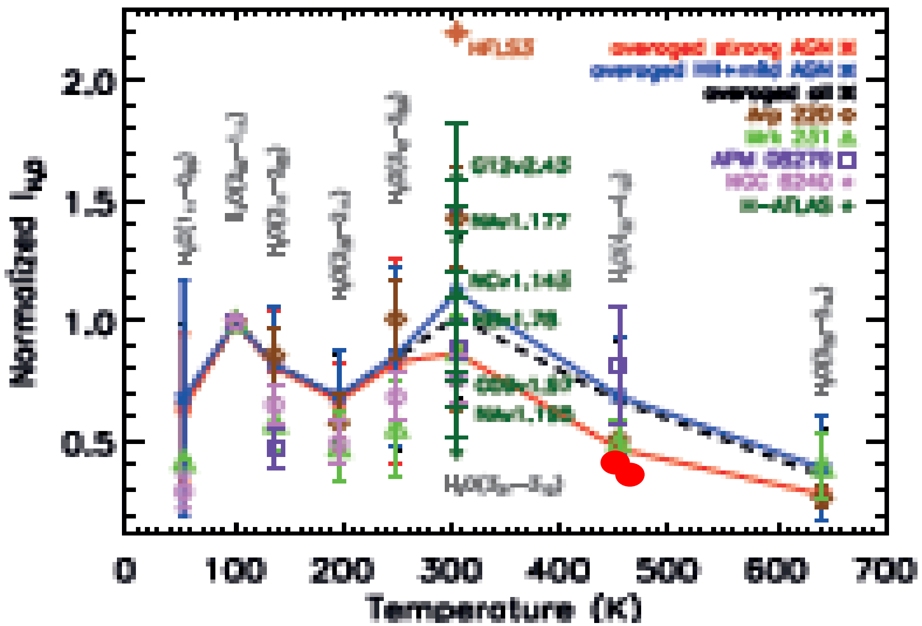
**from local ULIRGs to strongest high-z starbursts**

# $H_2O$ Excitation

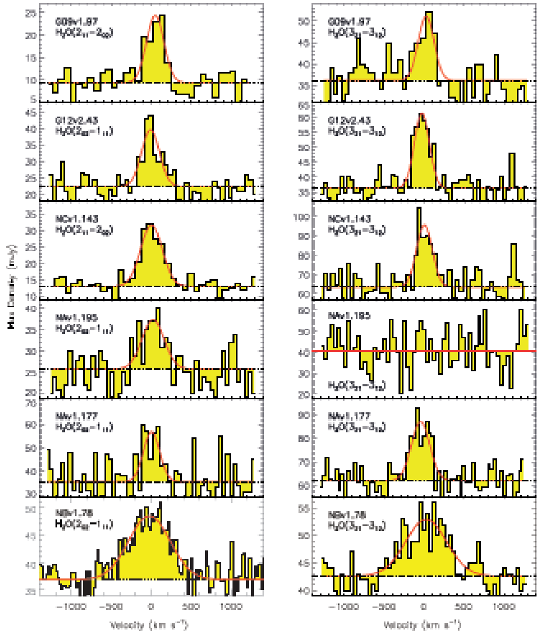
**Multi-line $H_2O$ observation**

- **J=2 lines (${E_{up}/k}$ ~ 100-130K)**
- **J=3 line $3_{21}$-$3_{12}$ ($E_{up}/k$ = 300K) 5/6 strong detections**
- **J=4 line $4_{22}$-$4_{11}$ ($E_{up}/k$ = 450K) Marginal detection of two sources**

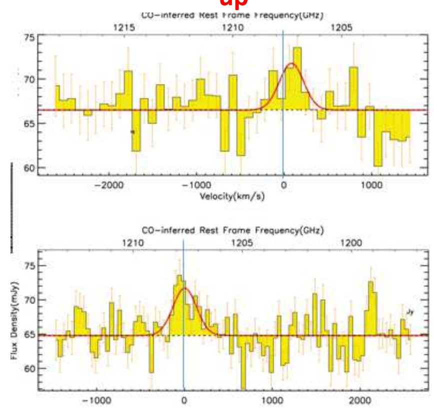
**→ relatively low excitation?**
**but roughly comparable to local ULIRGs**




**J=2 $E_{up}$~ 100K J=3 $E_{up}$= 300K**



**J=4 $E_{up}$ = 450K**

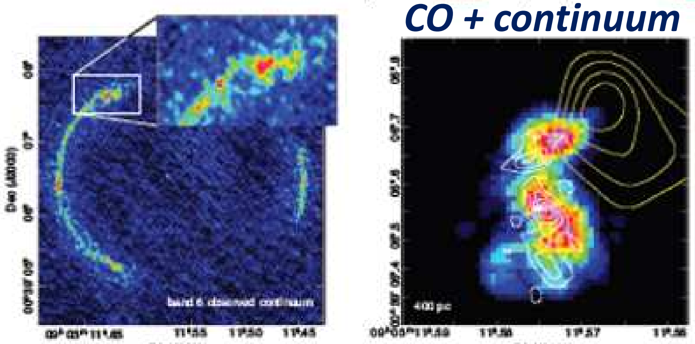


ALMA image of SDP81

in Science Verification

*ALMA Parnership 2015, Dye et al. 2015*

*CO + continuum*



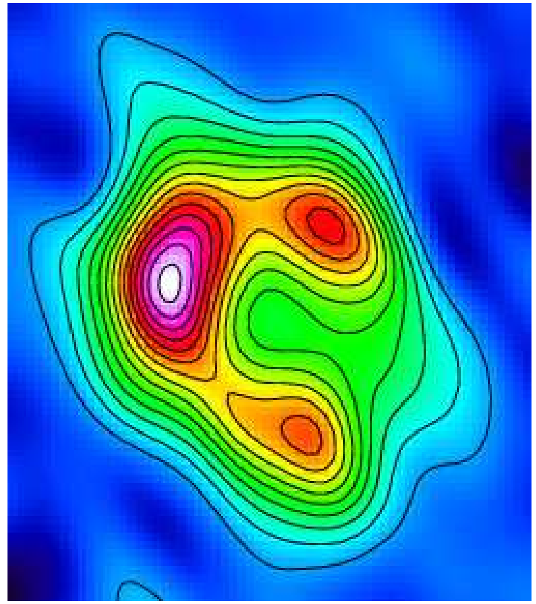

*Exceptionally extended SMG*

# High resolution images

→ Source structure/dynamics determination

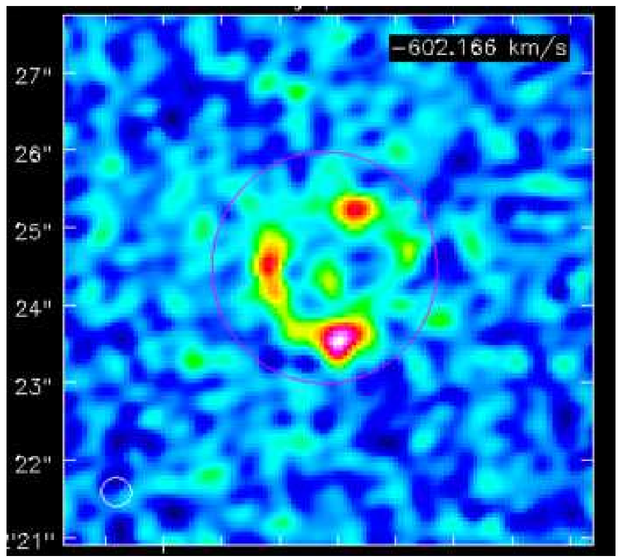
Images of stongly lensed H-ATLAS galaxies at z~3.5

Yang et al. in prep.



NOEMA continuum at 1.3mm, 0.5''

ALMA $H_2O$ at 2mm 0.3''



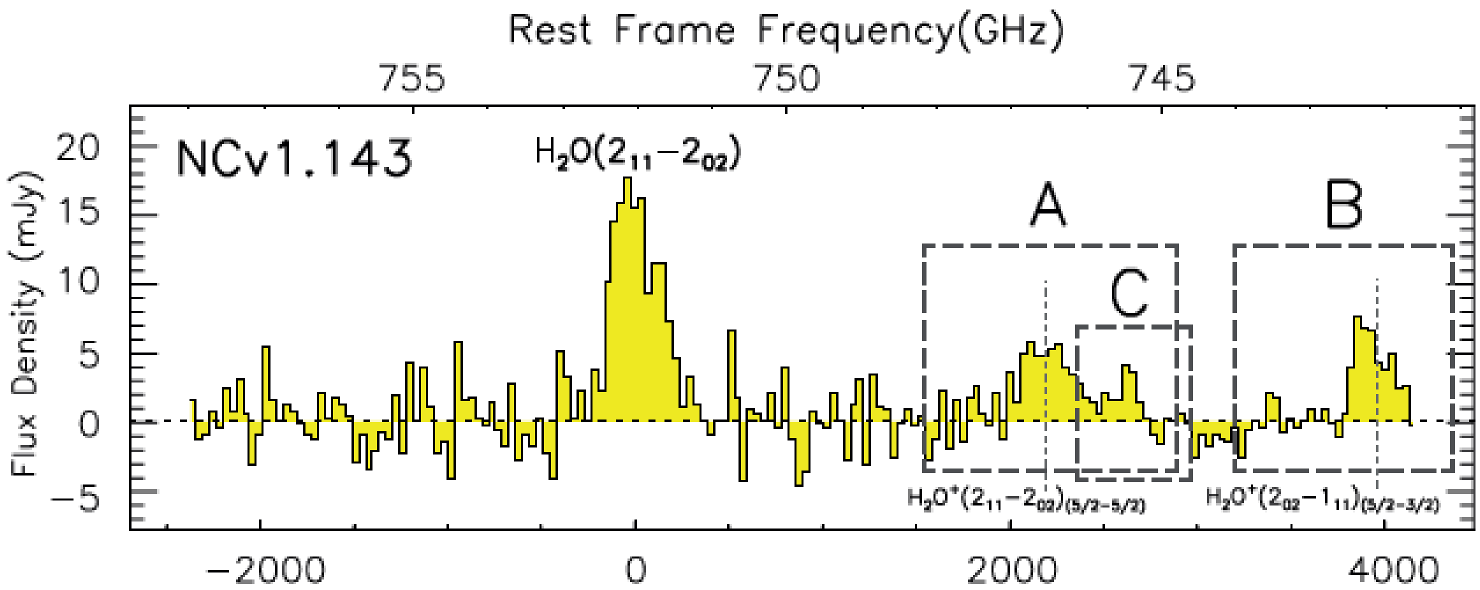
# Diagnostics

**Quite similar to local ULIRGs**
**Mostly possible with ALMA, but requiring large amounts of time**

- **Line excitation: IR, collisions ($H_2$, $e^-$), shocks, XDR…**
- **Galaxy structure: core(s)/nucleus/AGN, disk, mergers, (halo)**
- **Absorption lines → extended galaxy components, N($H_2$), ionization, etc. OUTFLOWS**
- **Chemistry, ionic (CR, XDR?), depletion/desorption**
- **Isotopic ratios**

# Detection of $H_2O^+$ in high-z Submillimeter Galaxies

**Strong emission of two $H_2O^+$ lines observable close to a key $H_2O$ line**
**Seen in local galaxies (also each**
**Easily detectable with NOEMA *Yang et al. 2016***
**Strong abundance of $H_2O^+$ is key for $H_2O$ chemistry**
**→ Cosmic ray ion chemistry**




$H_2O$ J=2 $H_2O^+$ $H_2O^+$

*Diagnostics 1*

# Line excitation
# (line ratios)

- **Far-IR pumping: most important (large electric dipole)**
  **→ higher energy levels**

  **$H_2O$** *Yang, Gonzalez-Alfonso et al. in prep.*

- **Collisions: $H_2$: first energy levels ($H_2O$)**
  **electrons: HF? Seen in emission in QSO BR1202** *(Lehnert et al. in prep.)*

- **→ Shocks: should need higher FIR lines**
  **XDR, etc.**

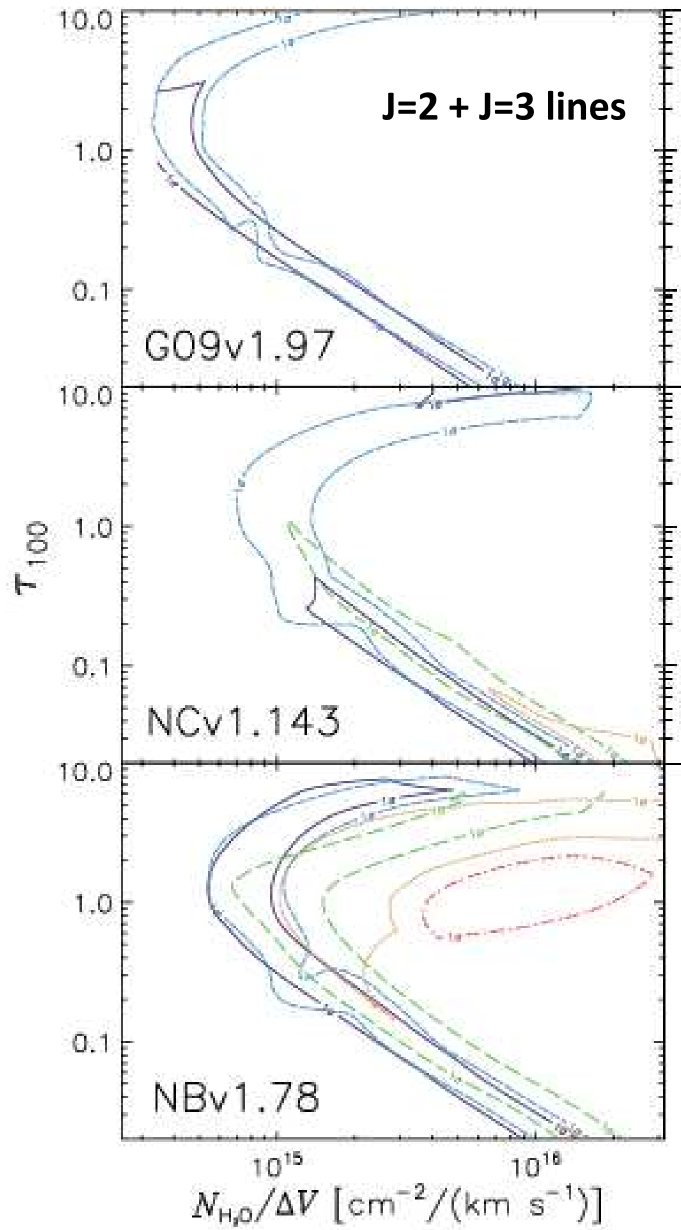
*Diagnostics 1*

# Line excitation
## (line ratios)

- ➢ **Far-IR pumping: most important (large electric dipole) → higher energy levels**
- ➢ **$H_2$ collisions (or $e^-$ → HF) may be important for lower levels**

**$H_2O$: modeling from line ratios gives constraints on main parameters: IR warm-dust temperature, FIR opacity, $H_2O$ column density…*(see talk by E. Gonzalez-Alfonso)***

- **J=2 (100K) + J=3 (300K) lines** *Yang et al. 2016, Yang,* **Limited constraints**
- **Additional J=4 (450K) line** *Gonzalez-Alfonso et al. in prep.* **Better constraints**



*Diagnostics 2*

# Galaxy structure

**Its determination needs systematic highest resolution images, mostly by ALMA, of a large sample of strongly lensed sources to account for structure variety**

- **Core(s)**
  **Main information from submm emission multi-lines + continuum**
- **Nucleus/AGN**
  **Very difficult to dissect. Try same methods as for local ULIRGs, but much harder**
- **Disk**
  **Extended disks should be traced by CO(1-0) and possibly by absorption lines ($H_2O$, etc.)**
- **Mergers**
  **One should find some traces of major mergers in a few cases**
- **Halo? $CH^+$?**
  ***See talk by E. Falgarone***

*Diagnostics 3*

# Absorption lines

**Should mostly trace extended, low density galaxy components. They are essential for that. ALMA is often needed especially for broad, weak lines. Not yet many results in high z (lensed) SMGs**

**They well trace $N(H_2)$ when abundances may be estimated, e.g. HF**

**The combination of $H_2O$, $H_2O^+$ and $OH^+$ should well trace the ionization (CR rate) plus the molecular fraction**

**Identification and characterisation of OUTFLOWS is the major outcome of absorption lines ($CH^+$ *Falgarone et al*., $OH^+$ *van der Werf et al.,* $H_2O$, $H_2O^+$ +, HF, etc.)**

# Chemistry/Abundances

- **ionic (CR, XDR?)**
- **depletion/desorption**

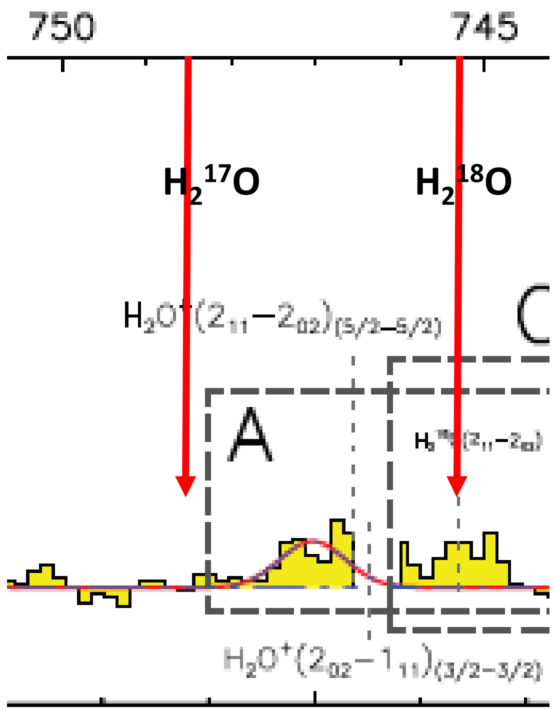
- **The large observed $H_2O$ abundance in ULIRG cores may reflect both the absence of ice mantles in warm gas and an efficient CR ionic chemistry.**
- **The strong $H_2O^+$ emission observed in H-ATLAS lensed sources points out to an efficient CR ionic chemistry**
- **Peculiarities of QSOS APM 0827 could reflect XDR influence?**

*Diagnostics 5*

# Isotopic ratios

**Difficult measurements; do need ALMA sensitivity**

**E.g. Recent ALMA ~5$\sigma$ detection of $H_2{}^{18}O$ in an H-ATLAS strongly lensed source, while there is no hints of detection of $H_2{}^{17}O$** *(Yang et al. in prep.)*



# Conclusions

**Young high-z ULIRGs (SMGs/DSFGs) have many similarities with local ULIRGs. Therefore, studies of their hydride subm lines offer similar powerful diagnostics. For studying these lines in strong lenses, ALMA provides a sensitivity similar to Herschel for local ULIRGs.**

**But:**

1) **Their order-of-magnitude more powerful starbust, close to the stability limit, should warrant special properties in core dimension, outflows and their consequences.**
2) **Time consuming ALMA studies are just beginning.**

**Priorities for ALMA (and upgraded NOEMA) studies of hydride lines could be:**

- **Systematic studies of outflows through absorption lines, and coordinated studies of extended galaxy components and environment.**
- **Systematic highest resolution observations of a significant sample of standard lensed SMGs/DSFGs, for characterizing their structure and dynamics.**
- **Identification of a sample of strongly lensed SMGs/DSFGs with buried strong AGN, and efforts for dissecting their molecular nucleus properties.**
- **Isotopologue studies.**