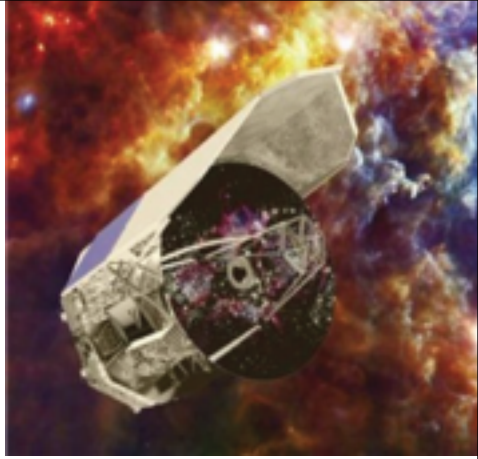



# Observations of high-redshift galaxies with Herschel and ALMA

*Alain Omont (IAP, CNRS & UPMC)*

*On behalf of H-ATLAS and other Herschel survey teams*

# OUTLINE

## Observations of high-redshift galaxies with Herschel and ALMA

- **Introduction: Herschel high-z heritage**

  - Herschel surveys have detected >5 $10^5$ high-z SMGs (x100s number)
    Various types, clustered. Detectable with PdBI → easy with ALMA

  - Herschel has detected more than 1000 high-z submm strong lenses
    Lenses increase the sensitivity by ~10 for studying high-z ULIRGs

  - But less than 100 (CO) redshifts: the third dimension is missing!

- **ALMA (and NOEMA): examples of programs with Herschel sources**

  0) CO redshift measurement

  1) Lens identification/properties

  2) Use of lens magnification for deep studies of high-z galaxies
     e.g. $H_2O$ ubiquitous emision
     Frequency surveys → high-z astrochemistry

  3) Identifying SMG proto-clusters

# Herschel surveys have detected >5 $10^5$ high-z SMGs

**Herschel SPIRE surveys (250-500 µm) have observed more than 1000 $deg^2$**
**(H-ATLAS 550 $deg^2$, HerMES ~350 $deg^2$ + SPT, AKARI-NEP, etc.)**

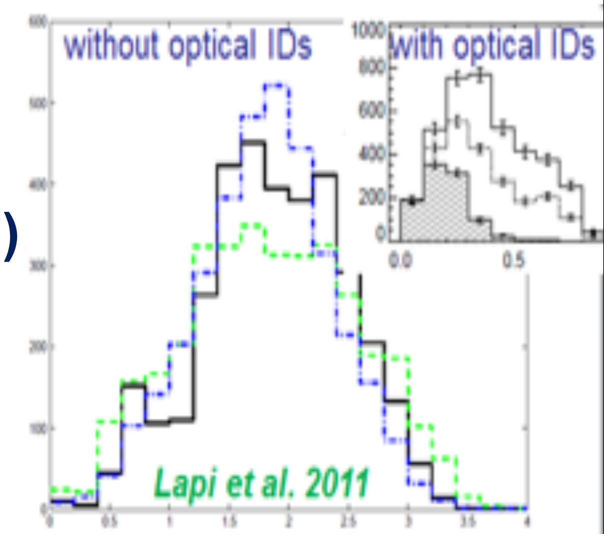
***vs* ~1-2 $deg^2$ by pre-Herschel submm/mm surveys (SCUBA, etc.) from the ground**

**Thanks to the FIR SED *("inverse K-correction")* they are extremely powerful for detecting high-z sources**

**Half are ULIRGs at z>1 (SFR >~ 300 Mo/yr)**

**→ >5 $10^5$ high-z Herschel submm galaxies (SMGs)**

**Similar to SCUBA 850µm SMGs, but slightly warmer on average**



# Half a million of high-z SMGs

Treasury for decades of high-z studies

Extreme SFR: merger starbursts or extreme main sequence
Most luminous (LFIR>$10^{13}$Lo, HyLIRGs) → maximum starbursts

Already large stellar mass at peak of star formation → progenitors of massive galaxies today: ellipticals or groups

Various (rare) types: $T_{dust}$, AGN, metallicity, various merger stages, structure, outflows, etc.

Trace evolution of massive galaxies. Specially important at highest redshifts (rare)

Highly clustered. Trace dark matter halos → large structures

Easily detectable in CO and continuum at PdBI → easy ALMA comprehensive studies

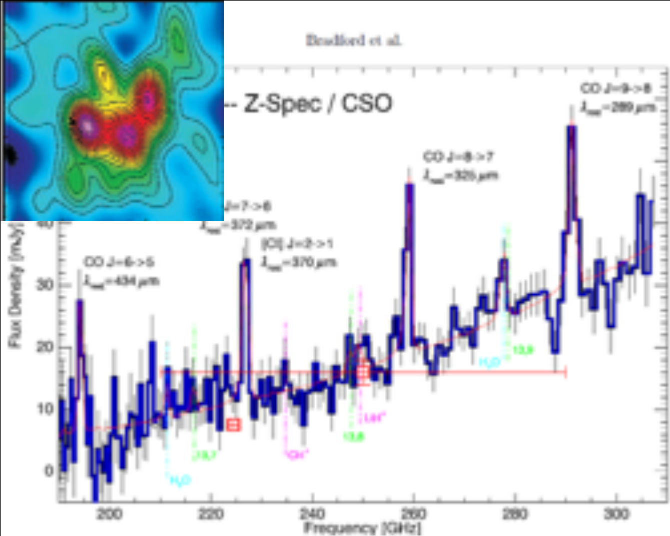
## Herschel has detected >1000 high-z submm strong lenses

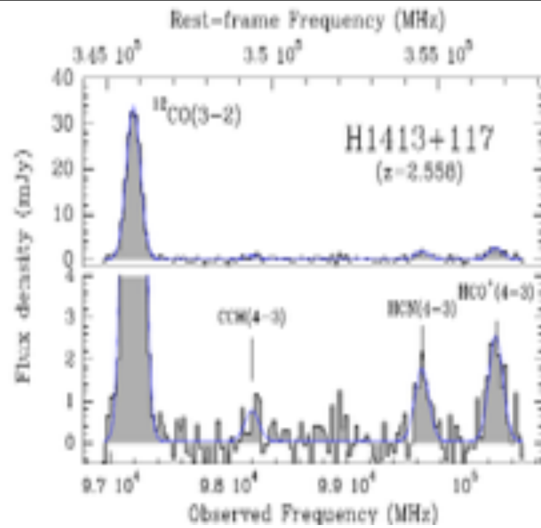
*See talks by Nicole Nesvadba and Daniel Schaerer*

**Very strong sources**

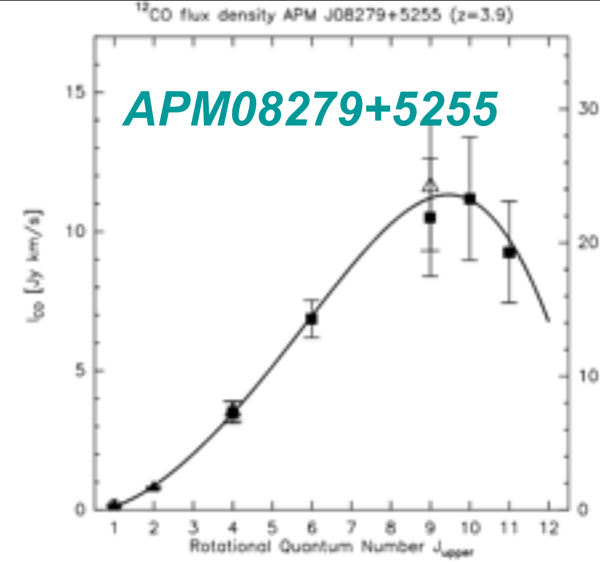
- $F_{250\text{-}350\text{-}500\mu m}$ >~100 mJy,
- $F_{850\mu m}$ >~25mJy,
- $F_{1.2mm}$ >~10mJy

**Strongest lenses increase the sensitivity by >~10 for studying high-z (LIRGs/)ULIRGs**




Cloverleaf

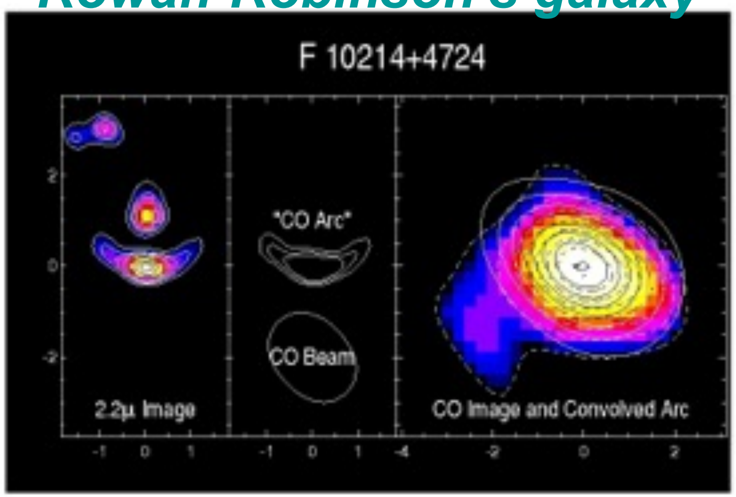



APM08279+5255

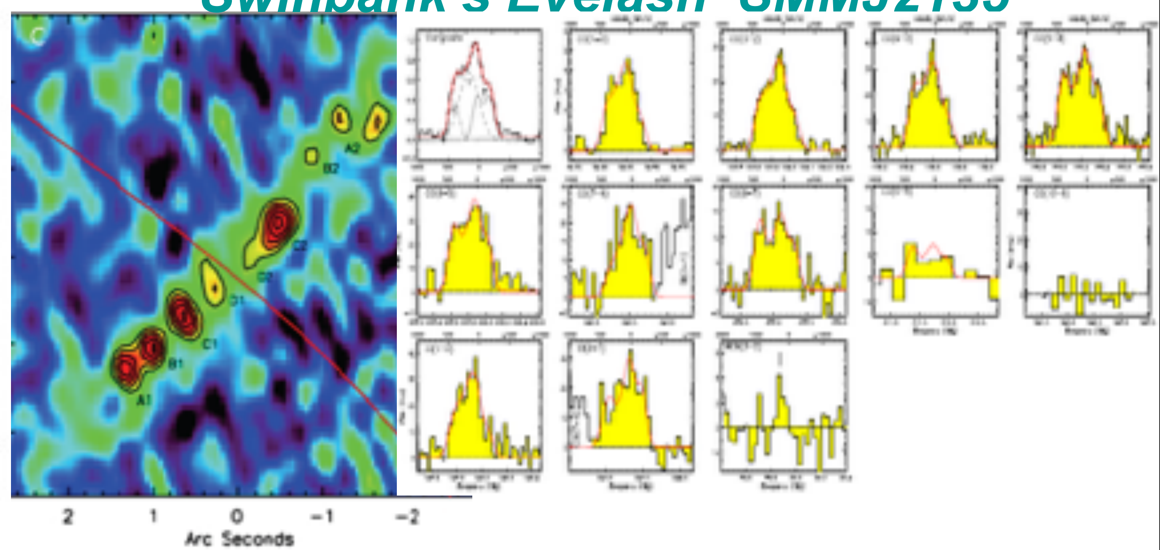
# The power of gravitational lensing

## Since 20 yr lenses have marked the frontier of high-z mm radioastronomy

Rowan-Robinson's galaxy




Swinbank's Evelash SMMJ2135



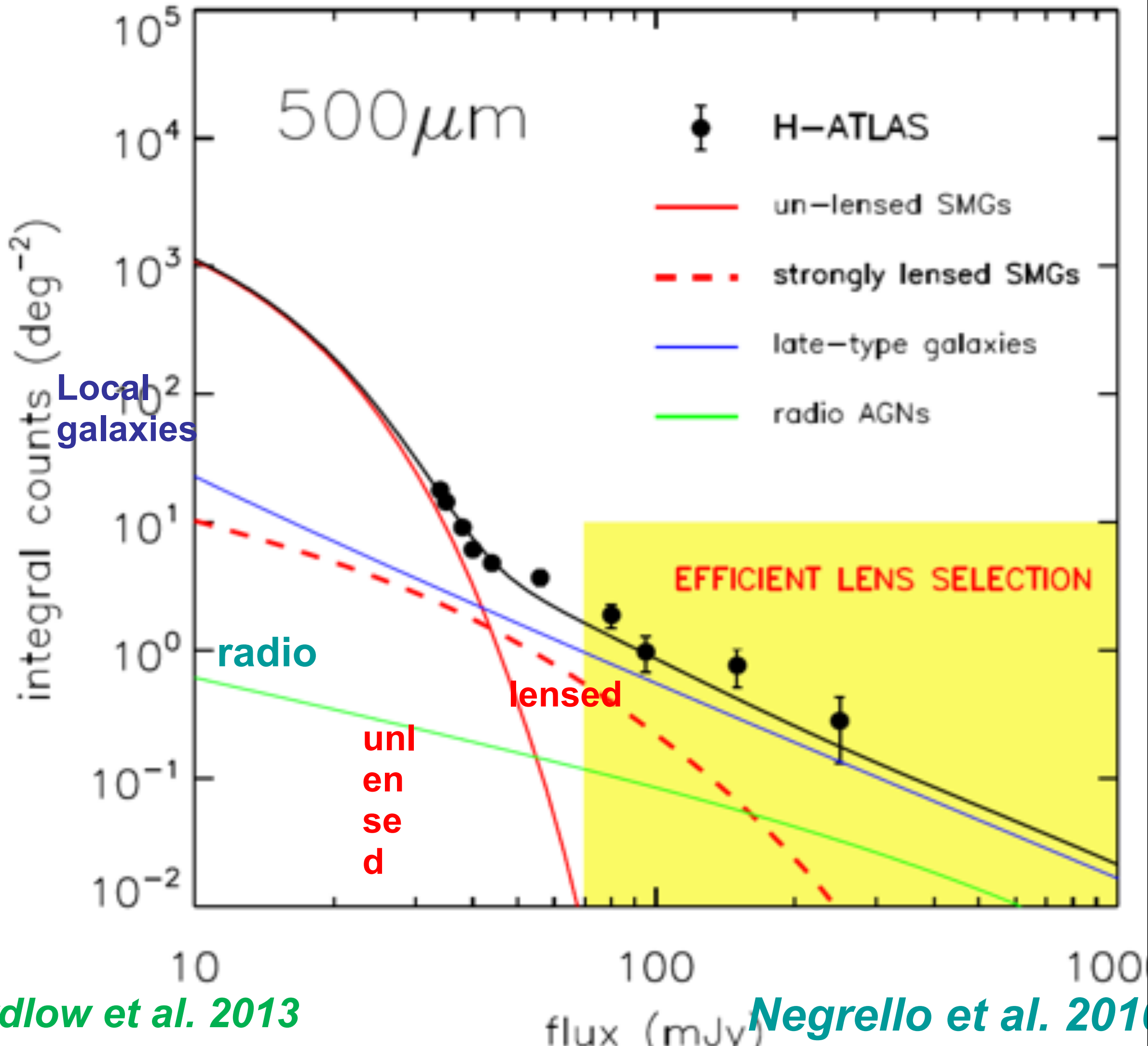
# Submm wide surveys are ideal for finding high-z lenses

- **High-z submm sources are very strong ('inverse K-correction')**

- ***Very steep unlensed counts***

à ***A significant percentage of the strongest SPIRE sources are high-z lenses***

à ***Very easy to identify from local galaxies (+ blazars)***




*See also Vieira et al. 2010, Wardlow et al. 2013*

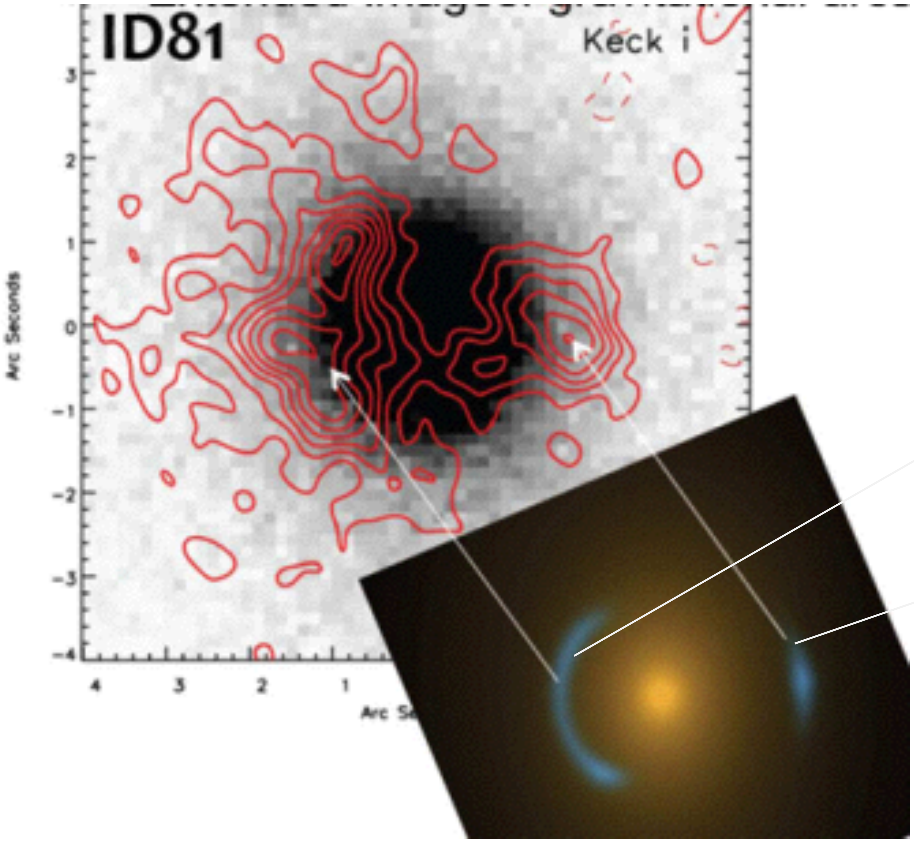
*Negrello et al. 201*

**SMA 870μm + Keck i-band**

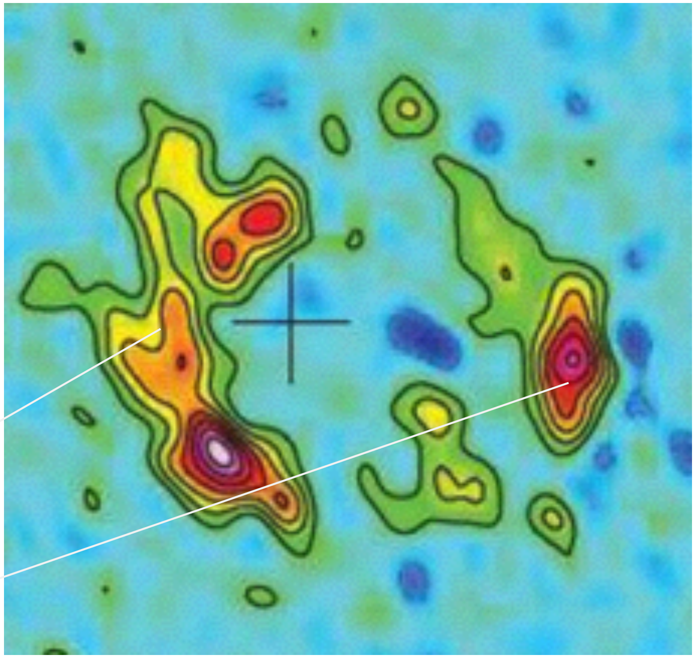
*Negrello et al. 2010*

**PdBI 1.2mm**

*Neri, Cox, Ivison priv. comm.*




*Lens template*



*First Herschel lenses (H-ATLAS SDP field)*

# Lensed image (Einstein ring) of H-ATLAS SDP.81

# Herschel has detected >1000 high-z submm strong lenses

- Very strong sources $F_{250\text{-}500\mu m}$ >~100 mJy $F_{850\mu m}$>~25mJy $F_{1.2mm}$>~10mJy
- Most deflectors are massive spheroids with a few spirals and groups
- Redshifts of the deflectors ~0.2 to >1 much higher than for the deflectors of optical lenses → evolution of dark-matter halos at z~ 1

à Strongest lenses increase the sensitivity by ~10 for studying high-z (LIRGs/)ULIRGs

**Half a million of high-z SMGs**
**A thousand of high-z lenses**

**Treasury for decades of high-z studies**

## But major drawbacks

- **Less than 100 (CO) redshifts have been measured: the third dimension is missing!**

- **Herschel (SPIRE) has a poor angular resolution (18”- 36”)**
  **Many sources are blended, especially at 500 µm**

- **ALMA and NOEMA can help on both points by efficiently measuring CO redshifts and providing snapshot images**

# Redshift determination of high-z SMGs with ALMA

➢ Redshift knowledge is absolutely essential for any study of high-z sources

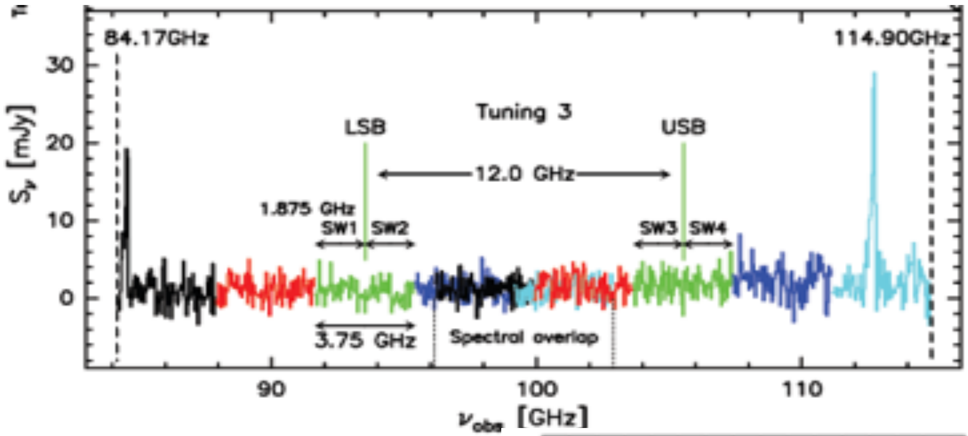
➢ Photometric redshifts of Herschel SMGs is often somewhat uncertain

➢ Optical/near-IR spectroscopy is difficult: faint sources, needs accurate position

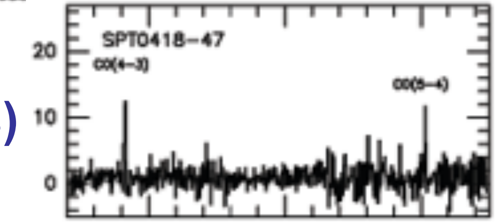
➢ ALMA is very efficient for blind (CO) redshift surveys of SMGs
e.g. Weiss et al. (2013, Cycle 0):

- 26 SPT strongly lensed SMGs
- 5 frequency set-ups to cover the whole 3mm Window
- 2 min per setup with 14-17 antennas
- Groups of nearby sources
- At least one strong line in 23 sources

à secure redshift for 70% of sample




➢ The same method remains efficient with full ALMA for unlensed Herschel SMGs: highest z, clustering, etc (+ lenses)




➢ NOEMA will be fully competitive with ALMA for this major goal

# Lens identification and properties

*See talks by Nicole Nesvadba and Daniel Schaerer*

- Very strong sources $F_{250\text{-}500\mu m}$ >~100 mJy $F_{850\mu m}$>~25mJy $F_{1.2mm}$>~10mJy
- Blind CO redshift measurement feasible at 30m-EMIR, PdBI, GBT, CARMA, CSO, APEX, LMT, etc.
- But ALMA and NOEMA are much more efficient and will be needed for measuring up to >~1000 redshifts *(see Weiss et al. 2013)*
- Cosmological interest because of higher z of lens dark matter halo
- Increased sensitivity for deep studies of various (rare) high-z (LIRGs/)ULIRGs
- ALMA and NOEMA fast snapshot imaging is also needed for discarding spurious blends

➢ Lens models and dedicated studies of prominent cases through ALMA or NOEMA high-resolution imaging
see e.g. SMA *Bussman et al. 2013,* PdBI *Ivison, Cox, Neri et al. in prep.*

# $H_2O$ at high redshift in Herschel lenses

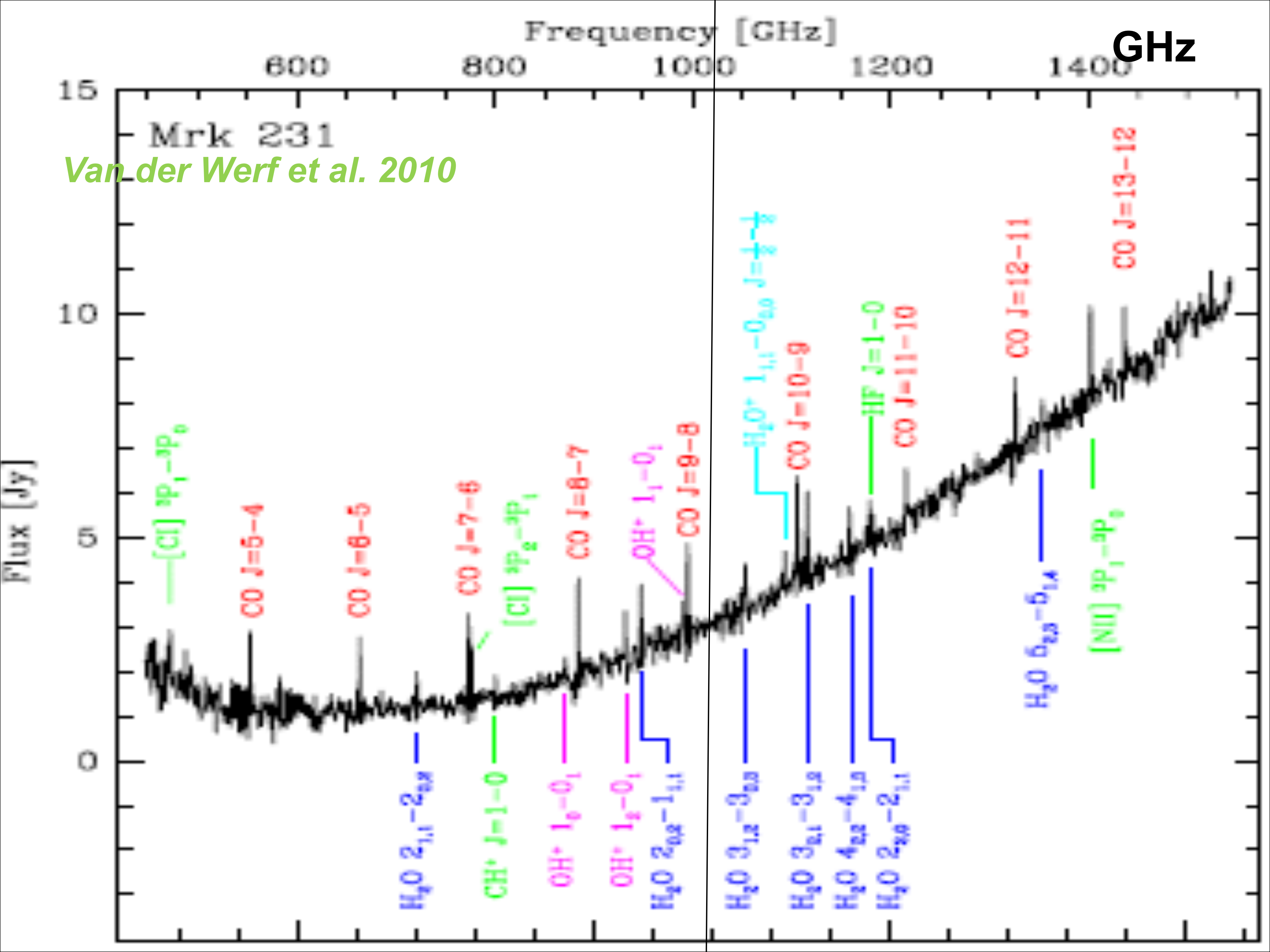
**- $H_2O$ lines have been found very strong by Herschel (SPIRE-FTS, etc.) in 40 local (LIRGs/)ULIRGs, with intensity ~0.3-0.5 next CO lines**

**- Similar situation is expected in high-z ULIRGs (and HyLIRGs up to 10 times more IR luminous without local equivalents), and thus $H_2O$ lines should be easily detectable in strong lenses.**

**First high-z detections of $H_2O$ in Herschel lenses *(Omont+ 2011, 2013, Combes +2012)* concomitant with confirmed detections in historical lensed QSOs: lensed: APM08279 z=3.9 *van der Werf+ 2011, Lis+ 2011, Bradford+2011,* Cloverleaf, other Herschel or SPT z~4-6 sources *Riechers+ 2013, Weiss+ 2013, Bothwell+ 2013.***

**$H_2O$ seems strong in all Herschel lenses**

**15 detections in H-ATLAS lenses at PdBI**



Frequency [GHz]
GHz
600
800
1000
1200
1400
15
10
5
0
Flux [Jy]
Mrk 231
Van der Werf et al. 2010
[CI] 3P1−3P0
CO J=5−4
CO J=6−5
CO J=7−6
[CI] 3P2−3P1
CO J=8−7
OH+ 11−01
CO J=9−8
H2O+ 11,1−00,0 J=3/2−1/2
CO J=10−9
HF J=1−0
CO J=11−10
CO J=12−11
CO J=13−12
H2O 52,3−61,4
[NII] 3P1−3P0
H2O 21,1−20,2
CH+ J=1−0
OH+ 12−01
OH+ 12−01
H2O 20,2−11,1
H2O 31,2−30,3
H2O 32,1−31,2
H2O 42,2−41,3
H2O 22,0−21,1

# Properties of $H_2O$ emission
# Comparison with CO

*PdBI CO: Cox, Ivison et al. in prep.*

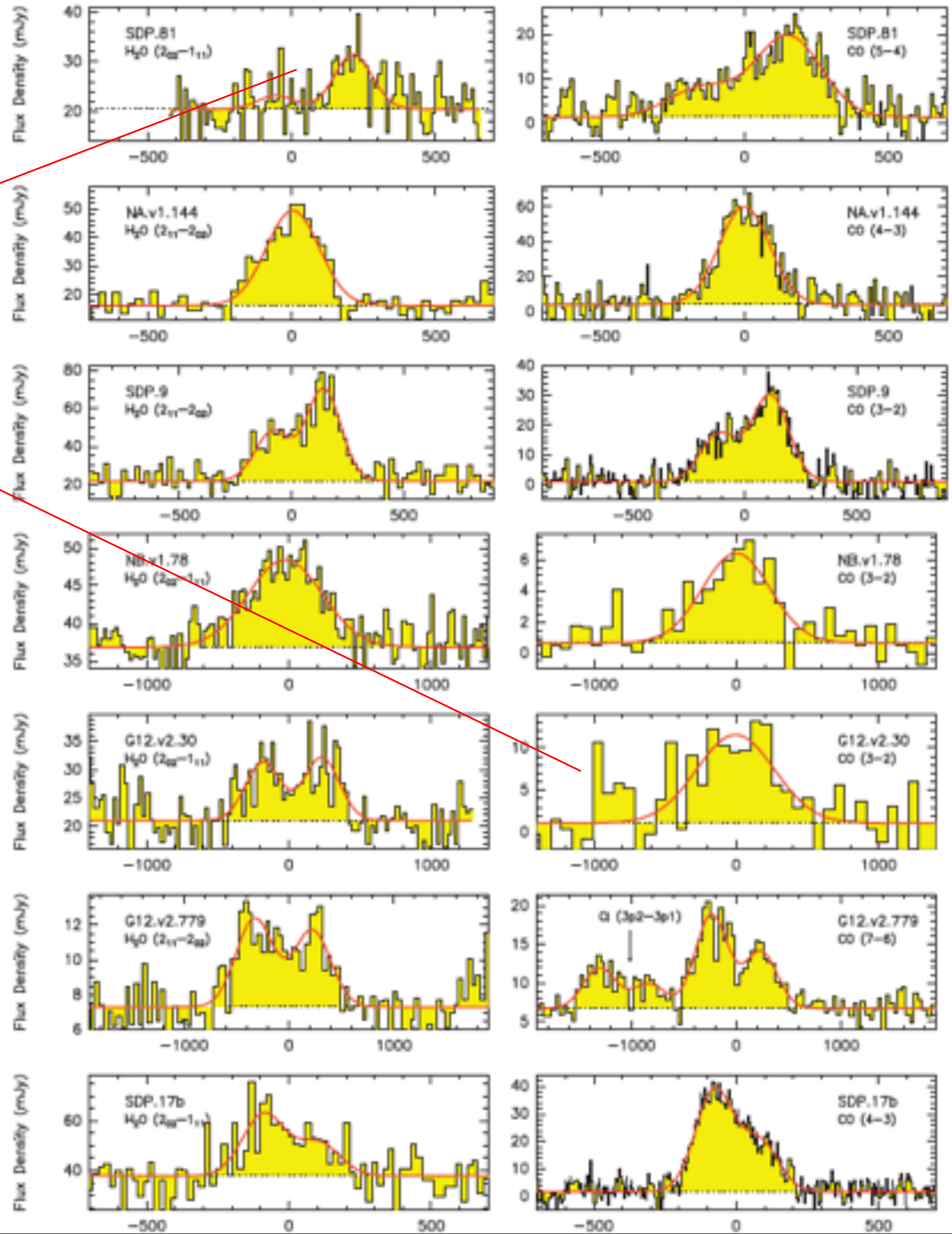
- Striking similarities of line profiles
  (noisy H2O in SDP.81
  noisy CO in G12.v2.30)

→ Same region of emission
→ No strong differential lensing

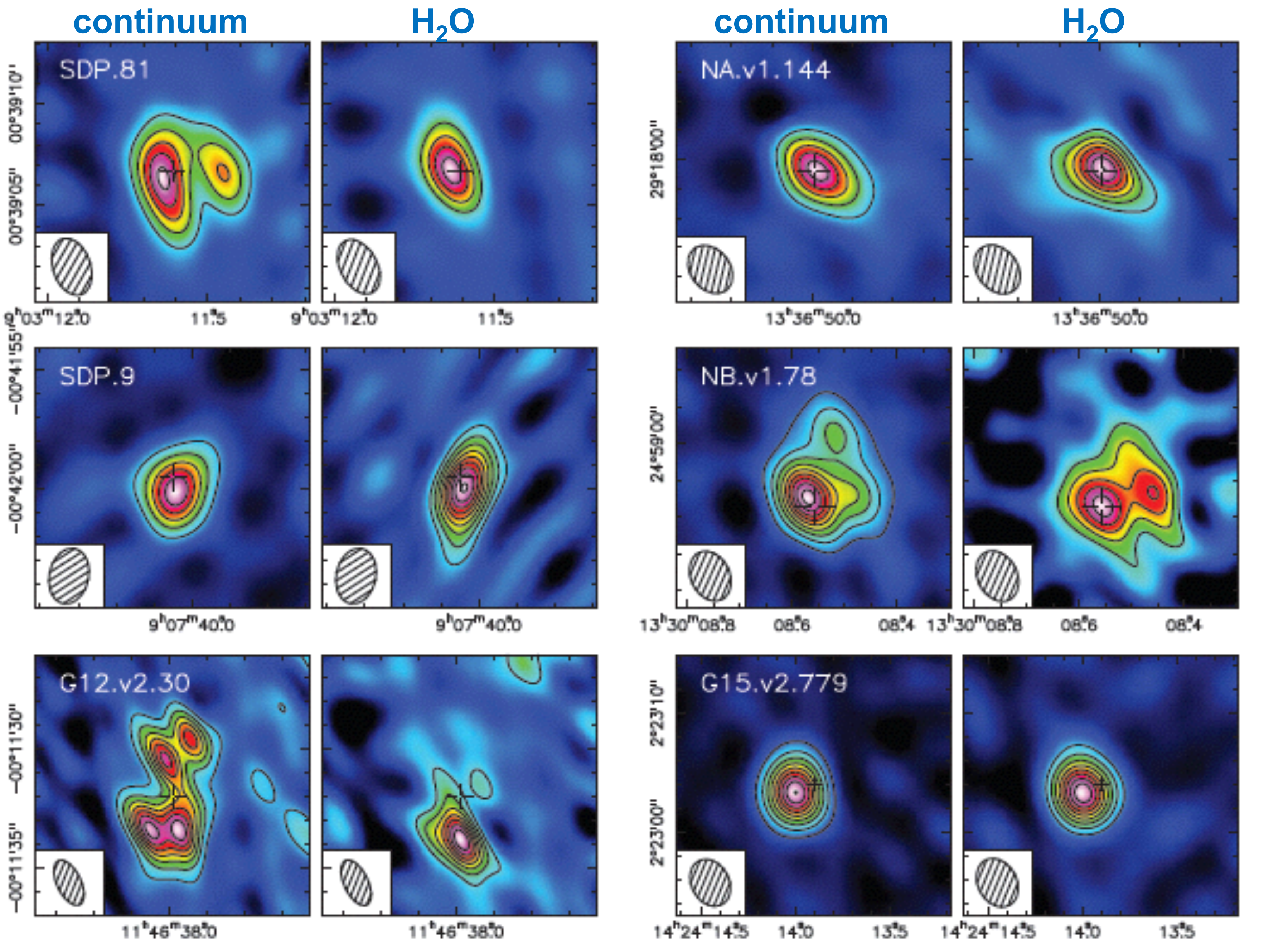
- Comparable $H_2O$ and low-J CO intensities
  (but CO at 3mm, $H_2O$ at 2-0.85 mm)

  Similar $H_2O$ and adjacent high-J CO lines ($H_2O$/CO ~ 30-50%)

- Similar strong $H_2O$ and continuum flux densities



# PdBI low-resolution maps



# Inferred conclusions for $H_2O$ in high-z ULIRGs

- The detection of $H_2O$ implies special excitation conditions and a warm dense gas, possibly similar to Arp220/Mrk 231 in an intense IR field with higher luminosity, but maybe different, more extended with shocks.

- The high $H_2O$/CO ratio makes it unlikely that the $H_2O$ emission originates in classical PDRs.

- The similarity of $H_2O$ and CO profiles is striking. The emission takes place in similar regions, with not much differential lensing

- However, the excitation and line formation of $H_2O$ are very complex , and this needs to be further explored by higher excitation lines of $H_2O$ at PdBI → ALMA

# Prospects for $H_2O$ studies in Herschel lenses (with ALMA)

➢ (Full) ALMA (and NOEMA) could easily detect $H_2O$ multi-lines in hundre
of Herschel high-z lenses

➢ Together with high-J CO lines, $H_2O$ lines will provide rich information about the conditions in the dense, warm, shocked ISM

➢ The full ALMA (and NOEMA) sensitivity will also allow detection of weaker lines such as:

- Absorption lines (seen in Arp 220 etc.)
- Outflows (seen in Arp 220 & Mrk231)
- Isotopologues $H_2^{18}O$, $H_2^{17}O$
- Other molecules detected in Mrk 231 & Arp 220: $OH^+$, $H_2O^+$ (allowing diagnostic of $H_2O$ chemistry), HF, etc.
- And many other molecules allowing, together with $H_2O$, further checks
of the warm, dense ISM