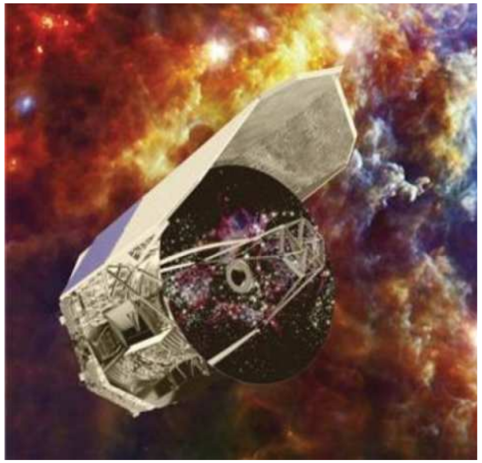


Herschel submillimeter lenses

H_2O, a new diagnosis of their dense cores

Alain Omont (IAP)

On behalf of H-ATLAS, HerMES & HLS Teams
and the IRAM Team (+ Chentao Yang)

OUTLINE

Strongly lensed high-z galaxies identified in Herschel wide surveys
H_2O, a new diagnosis of their dense cores

Using gravitational magnification
for studying Ultra-Luminous Infra-Red Galaxies (ULIRGs) at high redshift

- **Introduction**
  - Local ULIRGs.
  - Mm/submm studies at high-z →Herschel wide surveys: > 3 10^5 ULIRGs/HLIRGs

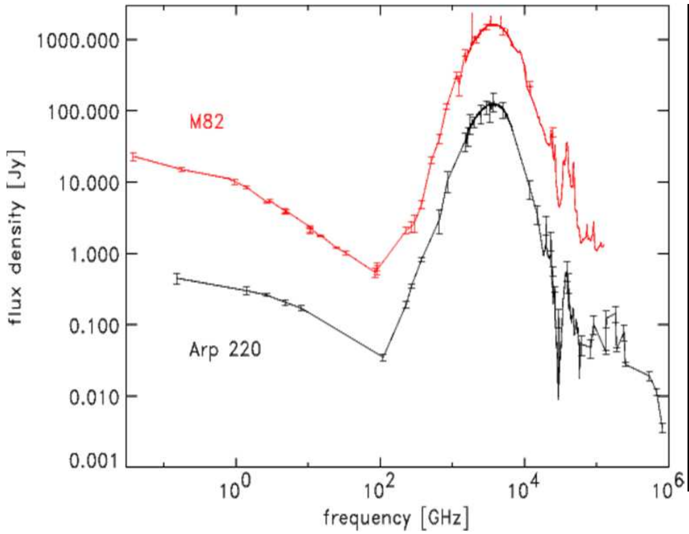
- **Herschel high-z strong submm lenses**
  - A new window on high-z dusty star forming galaxies
  - (- Studying strong lensing at higher redshift)

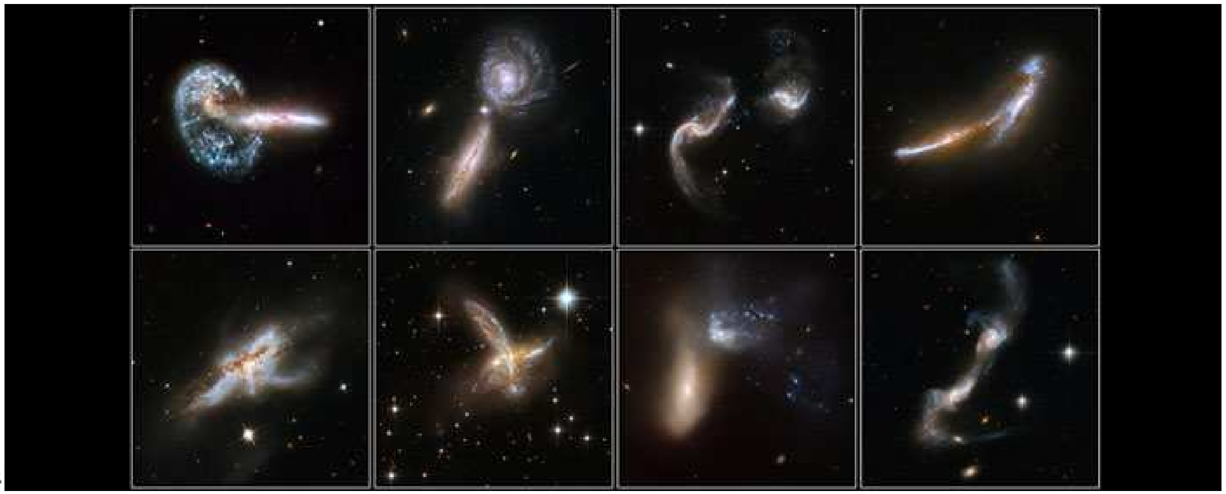
- **H_2O, a new diagnosis of dense cores of lensed high-z HLIRGs/ULIRGs**
  - Herschel submm spectroscopy of dense cores of local ULIRGs
  - H_2O mm/submm lines in 10 Herschel high-z lensed galaxies
  - Intrinsic H_2O luminosity → ~ $L_{IR}^{1.5}$
  - AGN interaction with molecular cores: H_2O excitation, chemistry, outflows
  - Prospects (→ALMA)

ULIRG 10^{12}Lo < L_{IR} < 10^{13}Lo HLIRG L_{IR} > 10^{13}Lo

Arp 220: prototype of ULIRGs?

- L_{IR} = 1.4×10^{12} *Lo*   SFR ~ 300 Mo/yr   Supernovae ~ 4/yr   >10^6 SgrB2 !
- thought to be in the final stage of merging
- radio & NIR imaging → double nuclei projected separation ~300 pc
- M_{H2} ~ 10^{10} M_o within central kpc
  in accord with simulations of galaxy mergers





HST images of colliding galaxies from the GOALS project

SMGs: strongest starbursts in the Universe

Important players of star formation at z >~ 2

- Revealed by SCUBA etc. surveys at 0.85-1.2mm
- Easy detection of dust FIR emission through « inverse K-correction »
- A few 10^{12}Lo: at least ULIRGs at z~1-2 (→ 1-4) → ~1 per 3-5 arcmin^2
- Massive. Mostly mergers or post-mergers. Mostly progenitors of ellipticals.
- Most exceptional HLIRGs 10^{13}Lo → ~1 per 50-100 arcmin^2 no local equivalent
- Only ~1000 SMGs available before Herschel (<~ 1-2 deg^2)
- <80 SMGs studied in CO lines: M_{H2}, (rotation) velocity, (post-)merger structure, M_{dyn}

→ Herschel surveys are detecting several 10^5 SMGs

HERSCHEL

Space Observatory, ESA (+NASA)

- **3.5m dish**

- **3 instruments:**

5

- **Cameras-photometers, FTS**
  - **- SPIRE 250-500µm** ***wide surveys → 1000 deg^2***
    ~4 x 10^5 high-z ULIRGs
  - **- PACS 70-160µm**

- **Heterodyne**
  - **- HIFI**

- **May 2009 → January-March 2013**

Herschel high-z extragalactic wide surveys

- **H-ATLAS 550 deg^2 relatively shallow**
- **HerMES 70 deg^2 deeper + 270 deg^2 very shallow**

both mostly SPIRE (250, 350, 500µm), close to confusion limit

- **Plus:**

- **PACS surveys: smaller areas, deeper**
- **HLS: lensing clusters,**
- **100 deg^2 overlap with SPT (South Pole Telescope)**
- **AKARI/NEP**
- **etc.**

Herschel surveys revolutionize the field of high-z submm galaxies

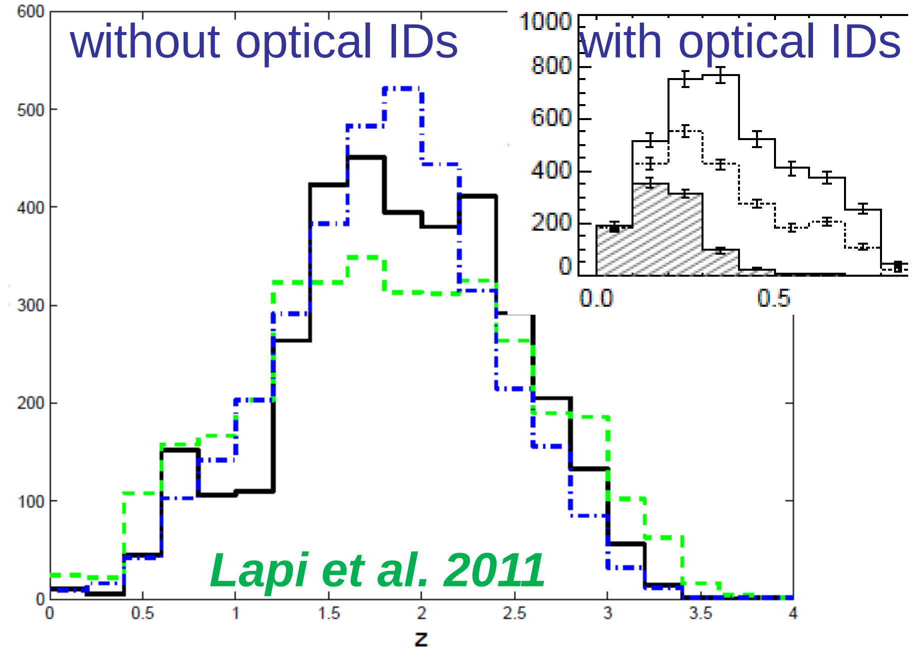
- **Several 10^5s high-z sources**

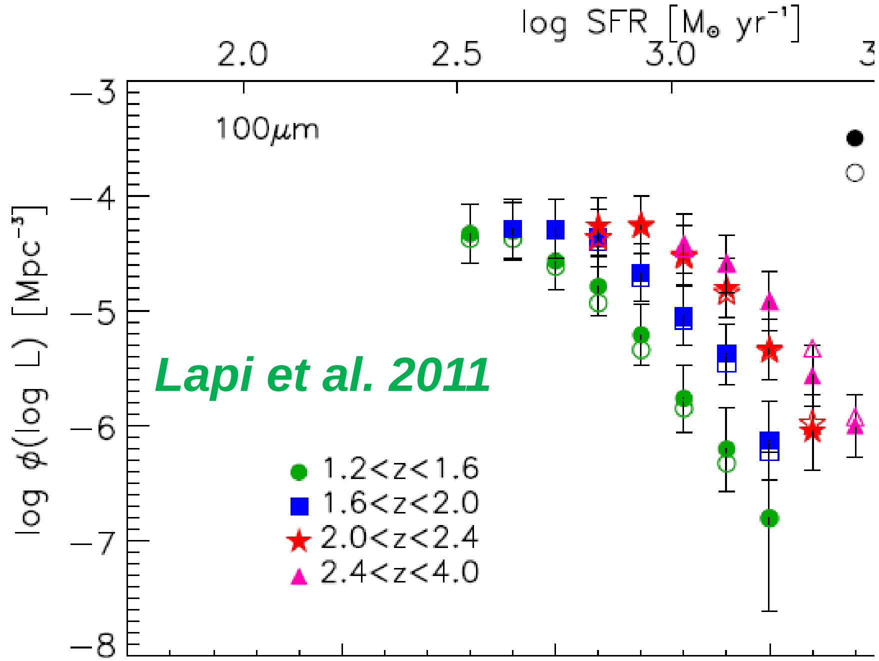
- **Half H-ATLAS sources have z>1 (inverse K-correction)**

- **All high-z sources are ULIRGs**
with SFR > 300 Mo/yr
and L_{FIR} > 10^{12} Lo

- **Some Herschel/SPIRE sources are warmer than SCUBA SMGs and not detected at ~1mm**
Some cold SMGs are not detected by Herschel

- **It is known that SMGs are highly clustered sources. This has been confirmed for high-z Herschel sources, tracing their dark matter halos (see e.g. Cooray+ 2010, Amblard+ 2011)**





Herschel lenses increase the sensitivity by ~10 for studying high-z ULIRGs

The power of gravitational lensing

Since 20 years lenses mark the frontier of mm radioastronomy with a handful of exceptional lenses (FIRAS10214, Cloverleaf, etc.)

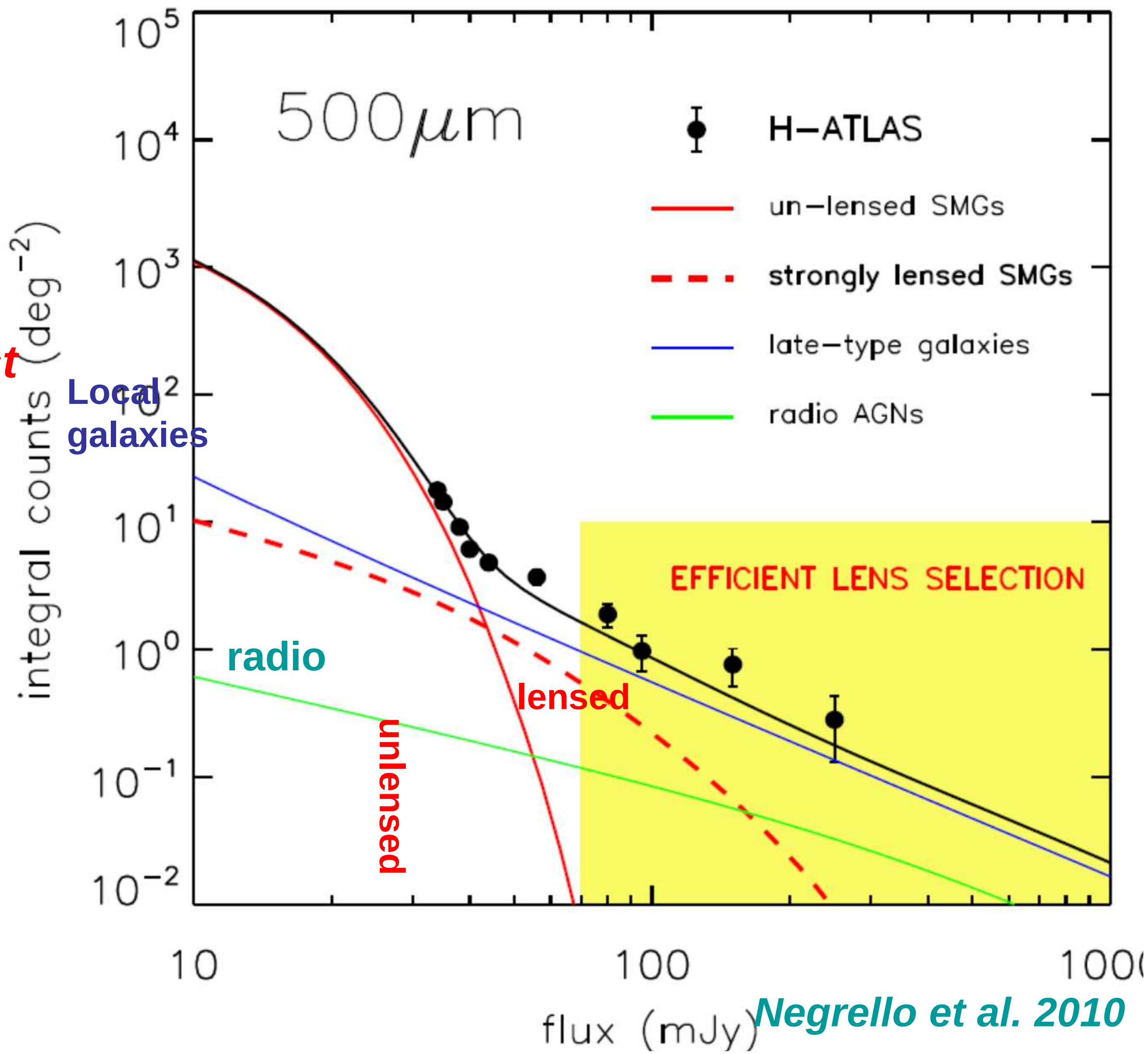
Submm wide surveys are ideal for finding high-z lenses

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

- *Very steep unlensed counts*

→ *Almost half of the strongest SPIRE sources are high-z lenses*

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



Negrello et al. 2010

Early studies of Herschel high-z strong lenses

- H-ATLAS SDP Field *Negrello et al. Science 2010*

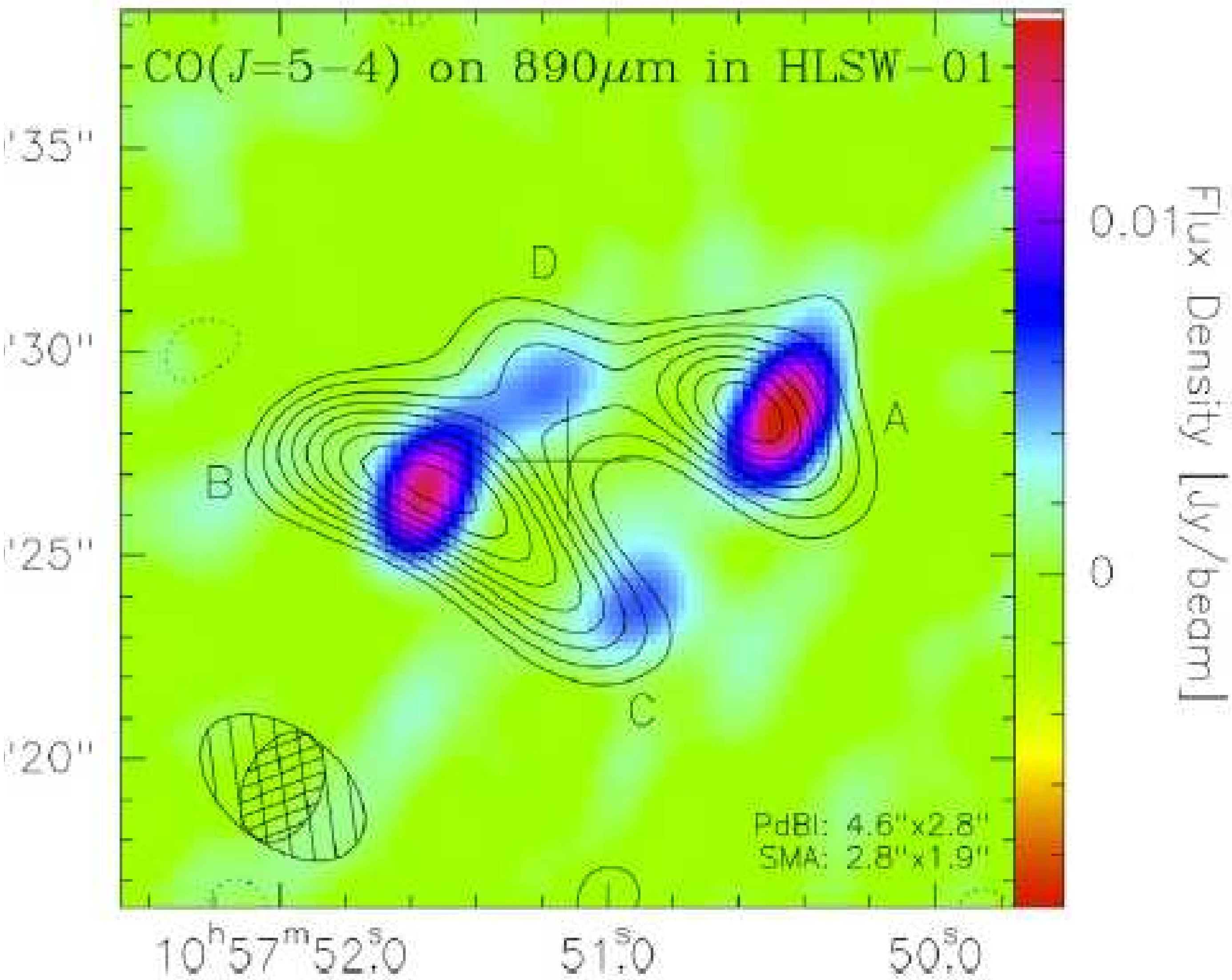
(+ a few other published papers, many unpublished works)

- ~14.4 deg^2 7000 sources 11 sources with $S_{500\mu m}$ > 100 mJy
→5 high z candidates → confirmed redshifts z = 1.5 – 3.4

- Clear cases of double-source SEDs
z~0.2-0.8 elliptical galaxy + high-z ULIRG

- Spectroscopic redshifts: difficult, almost all CO redshifts
  Broad band spectrometers: ZSpec@CSO+APEX, Zpectrometer@GBT
  IRAM(PdBI,EMIR@30m), CARMA: confirmation or direct determination

- Lensing
  Deflector identification: ell. gal.(+groups, clust.): SDSS, IR surveys,Keck..
  Lensed images: high resolution imaging: SMA, IRAM/PdBI, HST
  → ALMA

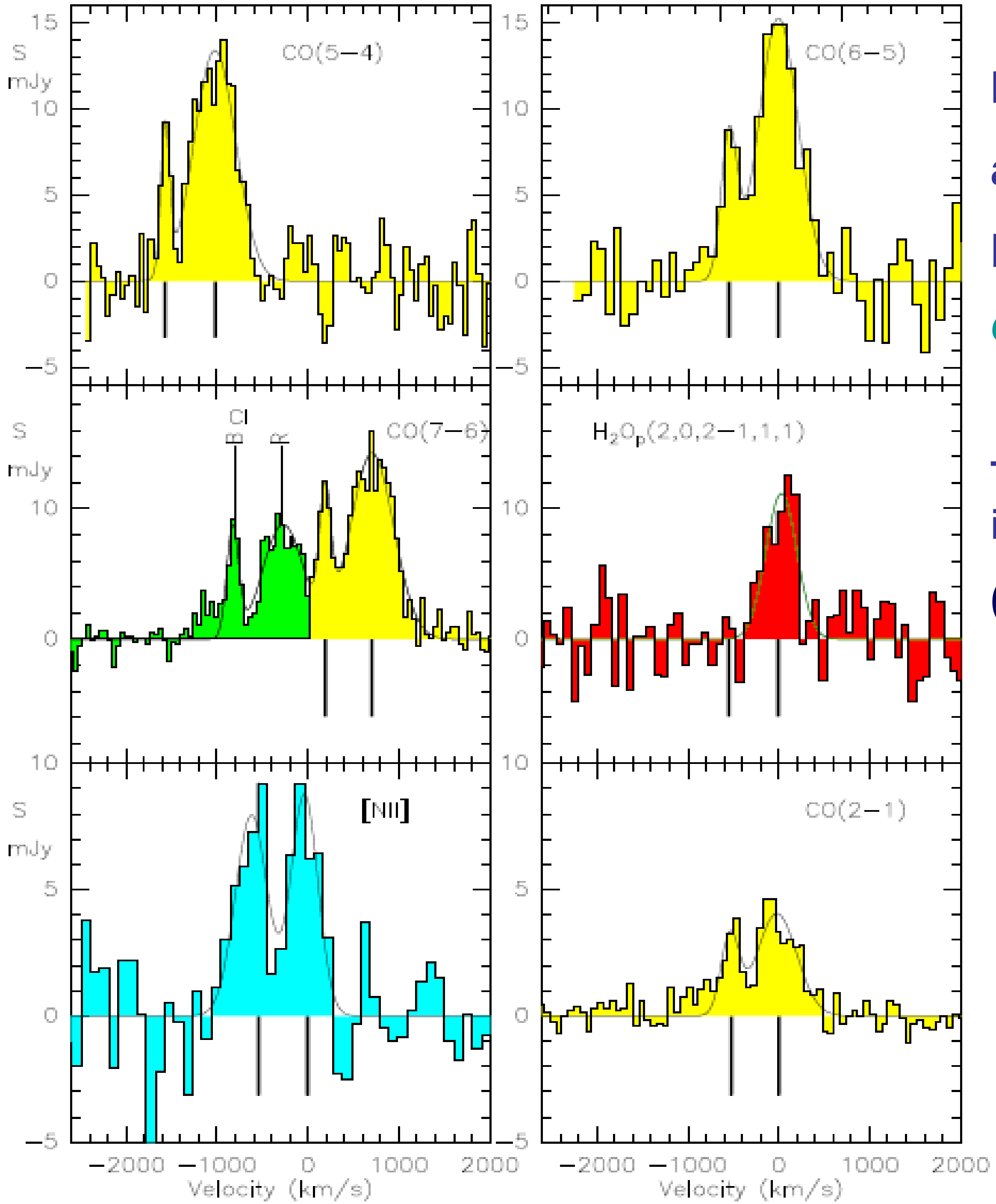


Map of the molecular gas in the 5-4 transition of CO (shown as contours) and the dust emission at 890 microns (color image) towards the lensed galaxy HLSW-01 at z=2.95. The line data were obtained using the Plateau de Bure interferometer and the dust continuum was measured with the SubMillimeter Array (SMA) in Hawaii.

The four spots of the lensed image are clearly seen with a maximum separation of ~9", revealing the internal gas dynamics in this system. From Riechers et al. (2011).

HerMES Lockman-01 = HLSW-01 PdBI + SMA *Riechers+ 2011*

(+Gavazzi+2011, Scott+2011)



HLSJ091828.6+514223

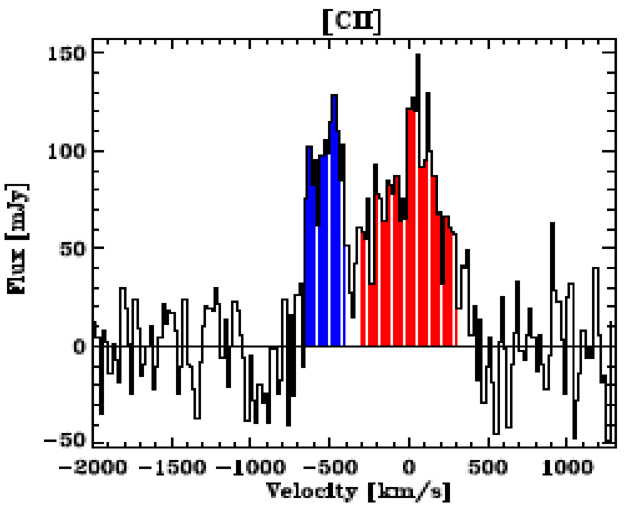
at z=5.243

behind the cluster A773

Combes+2012, Boone+ in prep

Two components with various intensities in different lines

(probably merging galaxies)



Prospects
for studies of Herschel high-z strong lenses

• A simple extrapolation of 5 lenses in 14 deg^2 H-ATLAS SDP yields ~200-300 similar lenses in total in ~1000 deg^2 Herschel surveys

• This number may be much increased by lowering the flux limits, e.g. by a factor >~5 for S(350μm) > 80 mJy

• Work is in progress for extensions of lens identifications:

- larger areas
- lower flux limits
- use of additional data, e.g. NIR surveys for identifying the deflectors

• One may thus expect **thousands** of Herschel high z lenses, including **~50-100** lensed sources in which the **magnification is > 10**
→ deep studies of high-z lensed sources (see below e.g. for H_2O, ALMA)

➢ An eventual goal is also to check the evolution of dark-matter halos of the deflectors
- Most deflectors are massive spheroids with a few spirals and groups
- Redshifts of the deflectors are mostly between z = 0.2 and 1, with a significant fraction at z>1. This is much higher than for the deflectors of optical lenses

H_2O, a new diagnosis of dense cores of lensed high-z HLIRGs/ULIRGs

- ***Herschel submm spectroscopy of local ULIRGs***
- ***H_2O mm/submm lines in 10 Herschel lensed galaxies***
  (plus 3 high-z QSOs)
- ***Intrinsic H_2O luminosity → ~ $L_{IR}^{1.5}$***
- ***AGN interaction with molecular cores: H_2O excitation, chemistry, outflows***
- ***Prospects (→ALMA)***

- ***H_2O is one of the most abundant molecules in the ISM***
  - ***In cold clouds practically all in ice on grains***
    abundance up to ~10^{-4}, 1/3 of total oxygen
  - ***Desorbed into the gas in hot cores***

- ***Practically impossible to observe from ground at z~0***
  - ***Except 22 GHz masers***
  - ***→ space: ISO/LWS, SWAS …***
  - ***→ high redshift** bringing lines into atmospheric windows*
    but H_2O lines are weak without lensing
    → full ALMA or <u>lenses</u>

- ***No confirmed detection of H_2O at high z prior to 2011***
  Except one maser at z~2

H_2O in local ULIRGs (Mrk 231)

H_2O is one of the most abundant molecules in the ISM

- In cold clouds practically all in ice on grains abundance up to ~10^{-4}, 1/3 of total oxygen

- Desorbed into the gas in hot cores

But it is very difficult to observe in the gas:

- Needs to be desorbed from the grains or formed in warm gas (X-ray catalysis on grains?)

- At low z: H_2O lines are completely absorbed by water in the Earth atmosphere → space

- At high z: H_2O lines are very weak in the absence of lensing amplification

No confirmed detection of H_2O at high z prior to 2011

Strong H_2O emission in the nuclei of local ULIRGs

Compact single- double-nuclei (+AGN) of major mergers

➢ Prominent FIR H_2O absorption lines in local ULIRGs (+AGN) such as Arp 220 , Mrk 231… (ISO; *Herschel* *Gonzalez-Alfonso +2011*)

Evidence for high H_2O abundance from $H_2{}^{18}O$, and high $^{18}O/^{16}O$ ratio with Herschel/PACS and SMA *(Gonzalez-Alfonso+2011, S.Martin+2011)*

➢ ***Herschel*/SPIRE: spectacular submm emission lines**

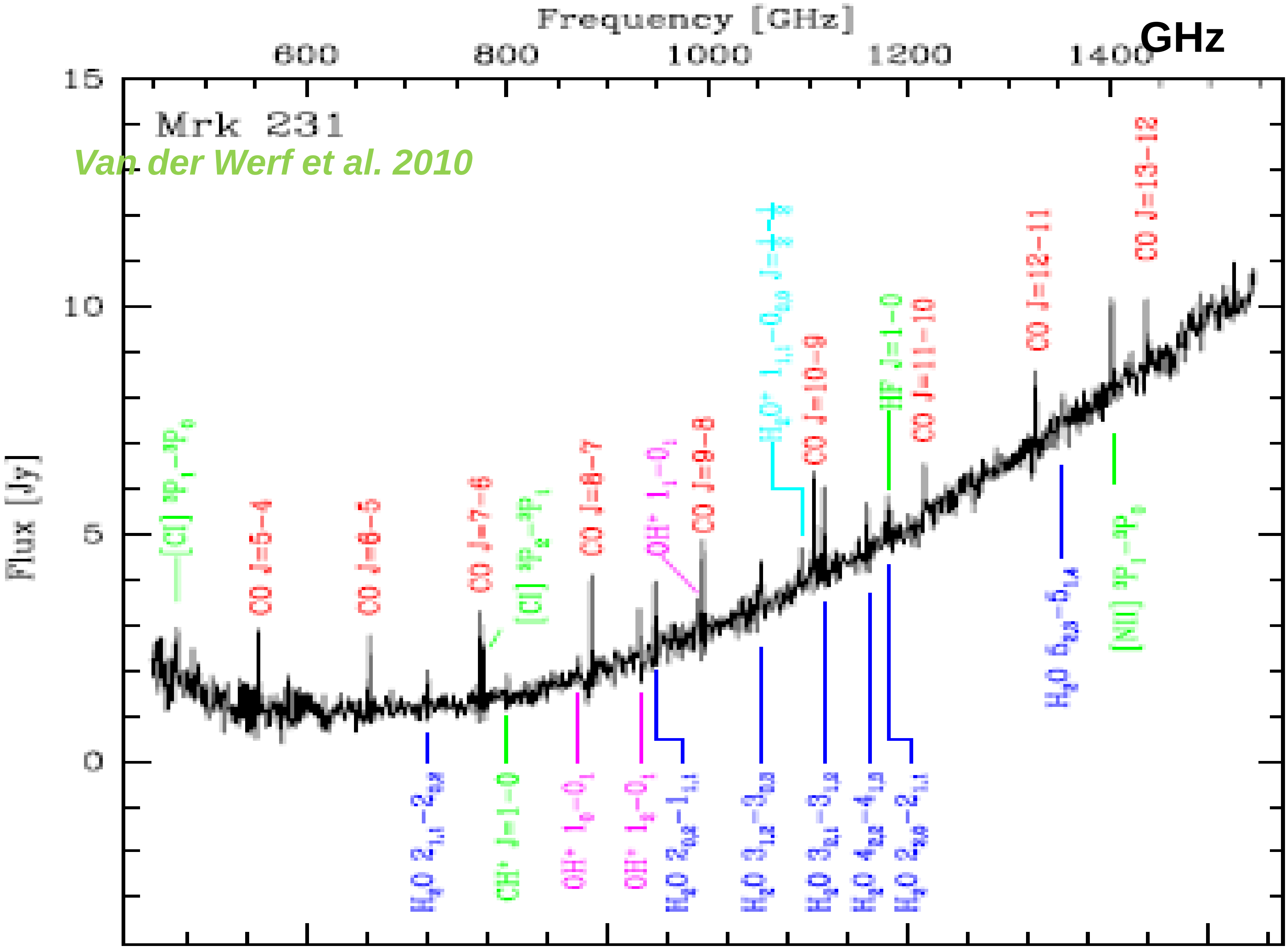
e.g.:

- **Mrk 231** (obscured QSO) *(van der Werf+ 2010)*

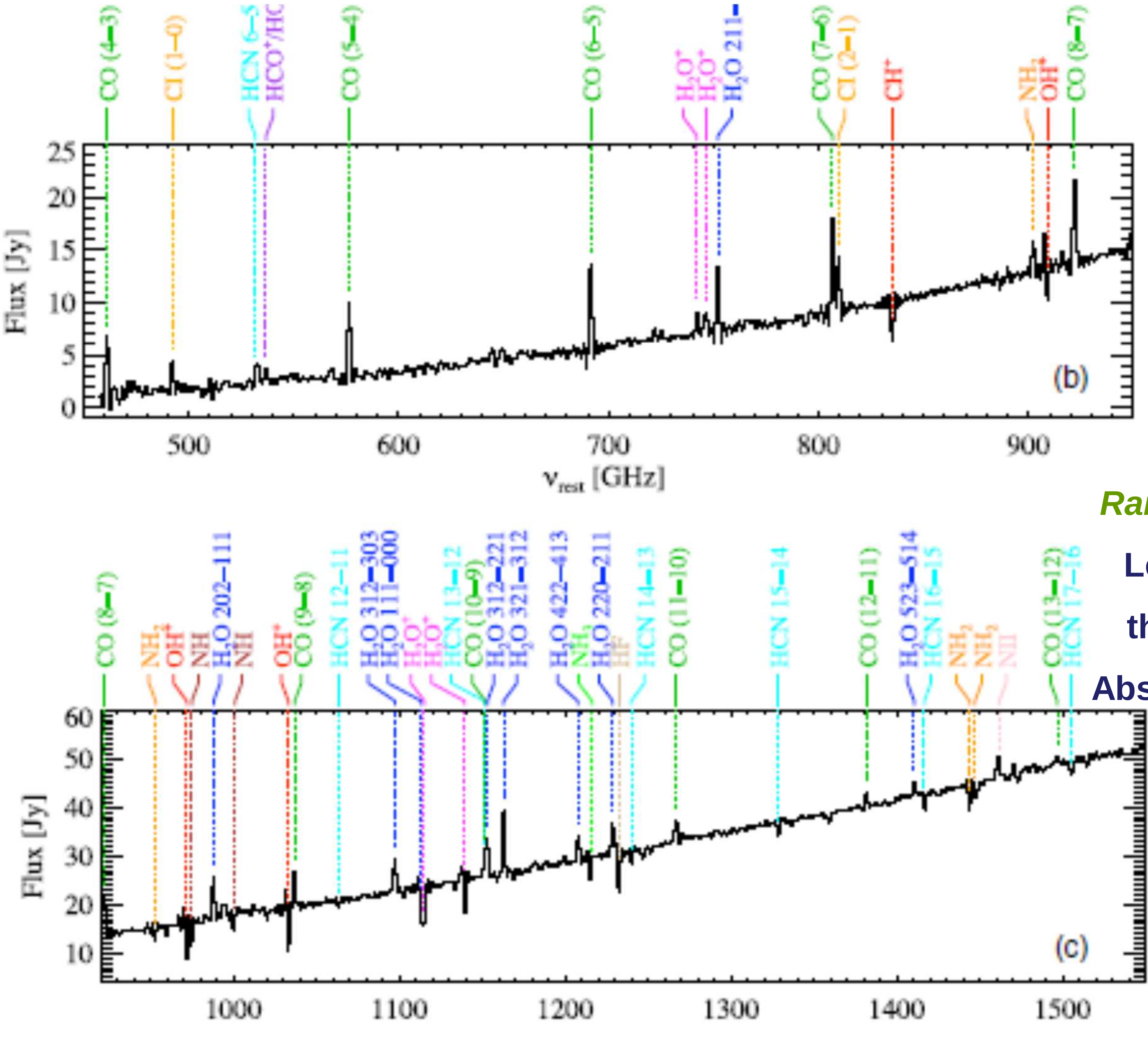
\- Several H_2O lines up to E_{exc}~600K
\- Strong lines comparable to CO (very different from M82 and PDR)
\- Plus high-J CO (strong), [CI], H_2O^+, OH^+, HF, CH^+, [NII], etc.

- **Arp 220** *(Rangwala+ 2011)*

\- Similar lines to Mrk 231 (although not strong AGN)
\- But weaker excitation; more lines in absorption (→ P Cygni profiles)



Frequency [GHz]
600
800
1000
1200
1400
GHz
15
10
5
0
Flux [Jy]
Mrk 231
Van der Werf et al. 2010
CO J=5−4
CO J=6−5
CO J=7−6
CO J=8−7
CO J=9−8
CO J=10−9
CO J=11−10
CO J=12−11
CO J=13−12
HF J=1−0
CH+ J=1−0
[CI]
[NII]



Arp220

Rangwala+2011

Less excited

than Mrk231

Absorption lines

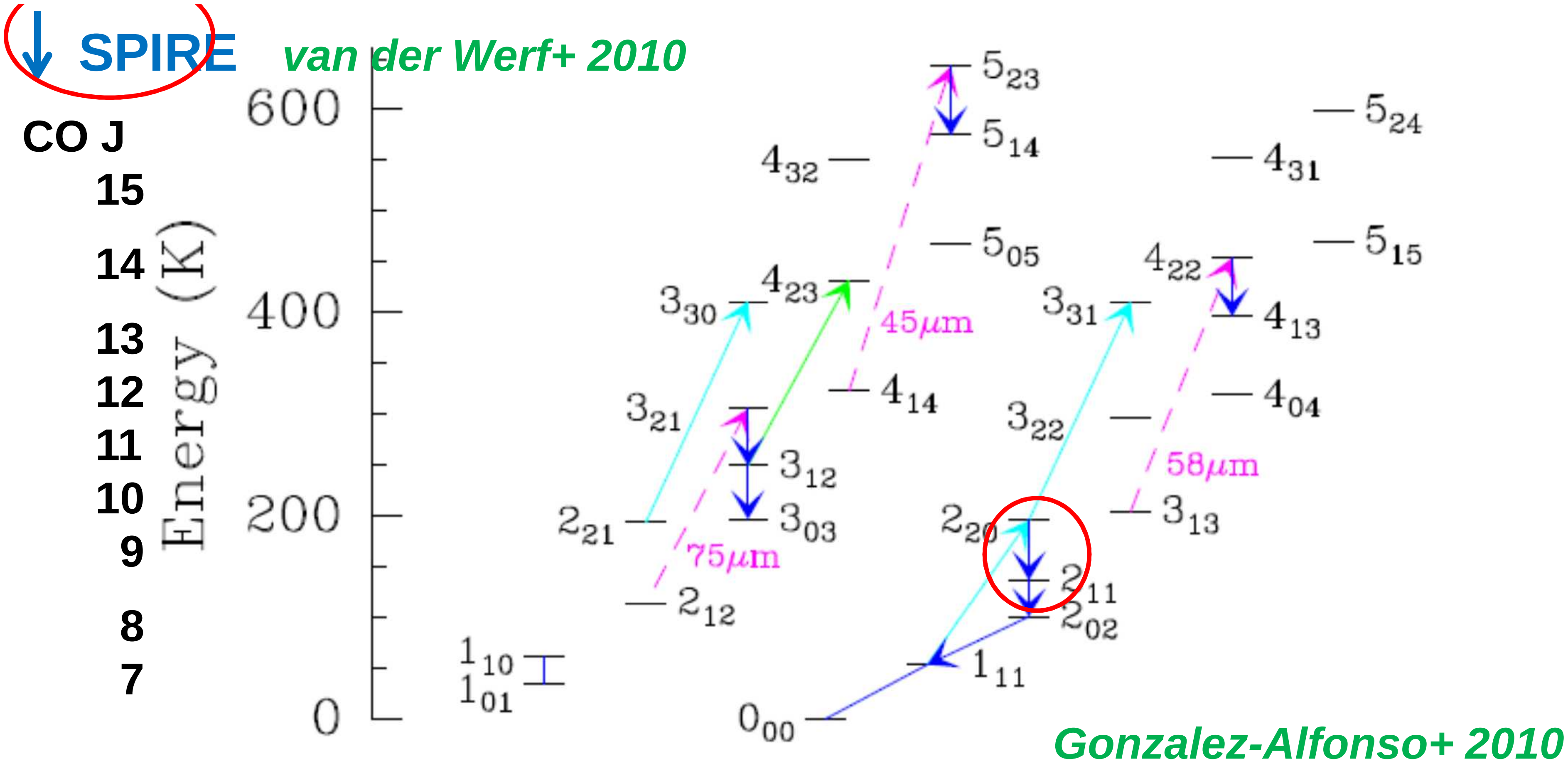


Fig. 2. Energy level diagram for H_2O, showing the detected/undetected (blue arrows/lines) lines with SPIRE, the line detected with PACS (green) and those detected by ISO (light blue). Dashed red arrows indicate the main pumping paths for the high-lying lines observed with SPIRE. Upward (downward) arrows: absorption (emission) lines.

Strong H_2O emission in the nuclei of Mrk 231

Implications (*Gonzalez-Alfonso+ 2010*):

- High H_2O abundance ($>\sim 10^{-6}$)
- Lower levels may be excited by warm dense gas (~100K, $\sim 10^6 cm^{-3}$), but likely FIR contribution
- Higher levels imply intense FIR excitation in few 100s pc
- Possible role of shocks, AGN (XDR), Cosmic Ray excitation but unclear
- Anyway difficult interpretation

→ High z

- Many objects similar to MrK 231 and Arp 220 are expected
- High-z HLIRGs up to 10 times more IR luminous → no local equivalents
- But very few detections of H_2O outside Herschel lenses

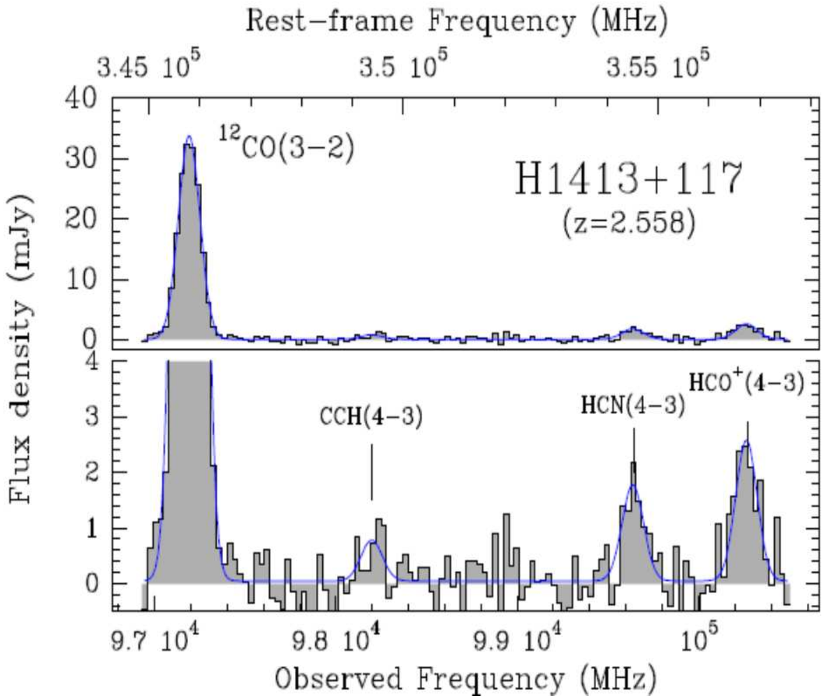
IRAM-Plateau de Bure Interferometer (PdBI)

H_2O mm lines in 10 Herschel lensed galaxies

H_2O lines must be easily detectable in many Herschel lenses

- Breakthrough by Herschel surveys
→hundreds of strong high-z lenses
(while only ~6 found before Herschel)

- **Unique opportunity for deep studies of high-z mm/submm lines**
As performed with classical mm lenses, e.g. the Cloverleaf



- H_2O line intensities are a significant fraction of that of CO lines in Mrk 231

- They should be easily detectable in strongly lensed similar high-z ULIRGs

PdBI detection of SPD-17b at 299GHz z=2.3

Omont et al. 2011 A&A 530, L3

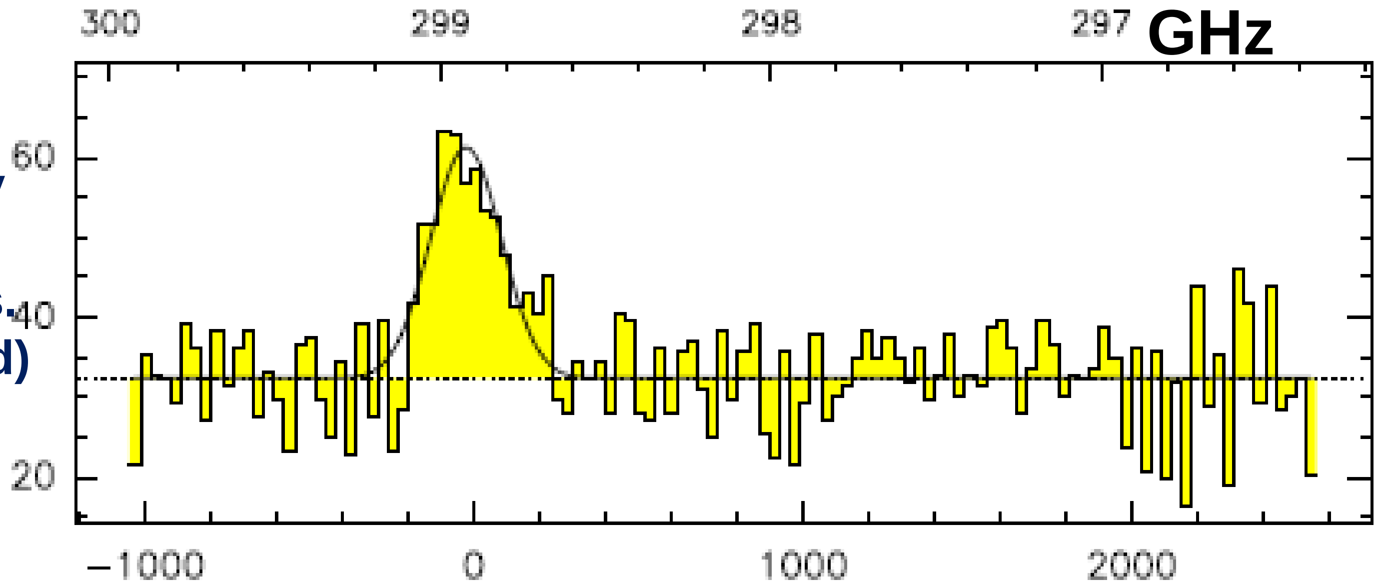
Observed parameters of the H_2O $2_{02}-1_{11}$ emission line in SPD.17b

ν_{rest} [GHz]	ν_{obs} [GHz]	z	S_ν [mJy]	ΔV_{FWHM} [km/s]	I [Jy km s^{-1}]	L^a [10^7 L$_\odot$]	L$'^a/10^{10}$ [K km/s pc^2]
987.93	298.93	2.3049 ± 0.0006	29	250 ± 60	7.8 ± 0.5	85 ± 0.6	2.5 ± 0.2

Compact D-conf.

Continuum 32+/-2 mJy

(+ extended A,B Confs. not yet fully processed)



Prospects for H2O studies in Herschel lenses (with ALMA)

➢ (Full) ALMA will easily detect H_2O multi-lines in hundreds 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 ISM of the compact merger nuclei

➢ The full ALMA sensitivity will also allow detection of weaker lines such as:

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

H_2O and OH Mega-masers

Megamasers are common but only in a fraction ~10/20% of local LIRGs/ULIRGs

Their luminosity increase with L_{IR} faster than linearly

H_2O 22 GHz masers come from very excited (~600K) levels

One H_2O mega-maser is known in a Type 2 QSO at z~0.8, another in highly lensed QSO at z~2.5 ***(Impellizzeri+2008).***

Both H_2O and OH mega-masers should be detectable in a significant fraction of Herschel lenses
Privilegiate HLIRGs

Other molecules and XDR/AGN diagnosis

As seen in local ULIRGs, many other molecules should be detectable In high-z lenses, as complementary diagnosis of dense, warm cores: HCN, HCO^+, HNC, CS, NH_3, HC_3N, H_2S, H_3O^+, CH^+, HF, N^+, etc.

OH^+ and H_2O^+ are specially interesting, because they are known good tracers of X-ray AGN chemistry

At low z OH^+ is fairly common at level of 50% of H_2O lines and traces energetic electron collisions (but H_2O^+ is much rarer) ***(Berciano-Alba + van der Werf priv. comm.)***

Both OH^+ and H_2O^+ show very deep P-Cygni profiles indicating massive molecular winds

Observation of OH^+ and H_2O^+ not so easy because rather high frequency
→ Preliminary PdBI project accepted to observe OH^+ and H_2O^+

Prospects → ALMA

Outflows: starbursts vs AGN

- **Massive molecular outflow in Mrk 231 seen in:**

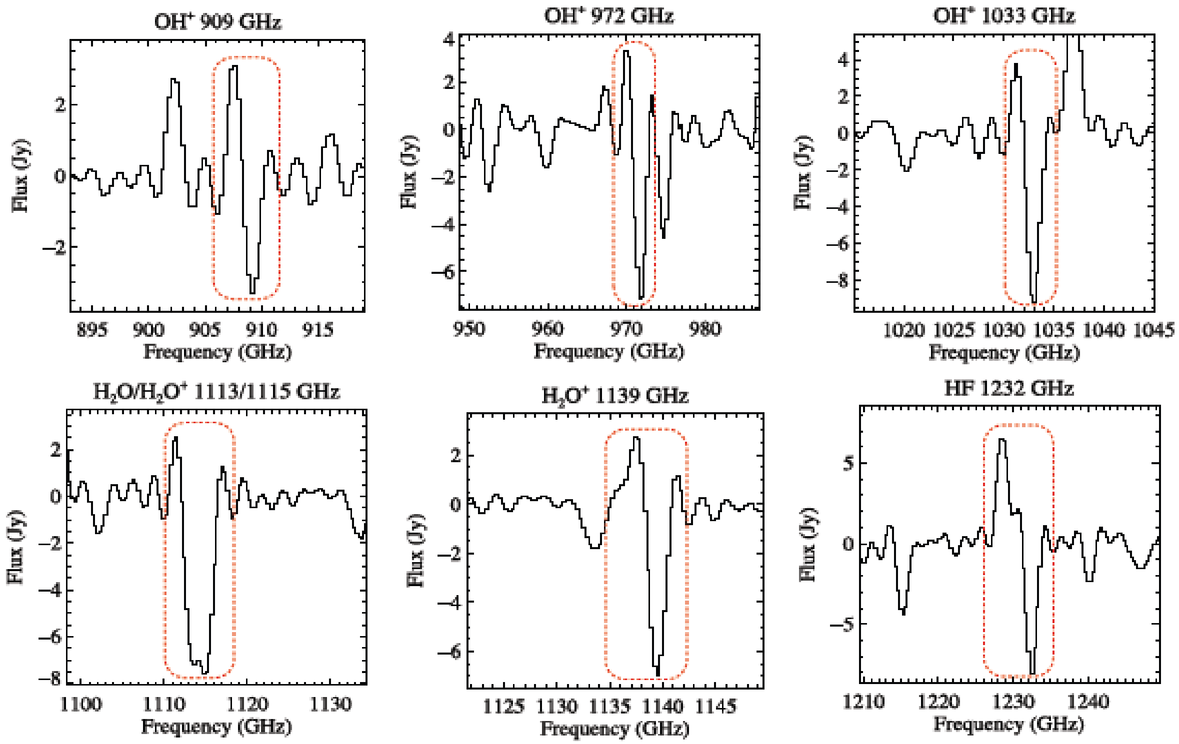
CO *Feruglio et al. 2010 :* **750 km/s and spatially resolved on kpc scale : 700 Mo/yr (> SFR)→ 10^7 yr**

OH *Fischer et al 2010* **: 1400 km/s**

- **Moderate outflow in Arp 220**

Rangwala et al. 2011

~200-300 km/s



ure 10. P Cygni detected in OH^+, H_2O^+, and HF lines, suggesting molecular outflow in Arp 220. The dashed region highlights the P Cygni profile

Such outflows should be common in high z ULIRG/HLIRGs

ALMA

50 x 12m dishes
+ ACA array 7m dishes

Summary

- Herschel surveys have observed ~1000 deg^2
- First lens identifications and intensive follow-up confirm that one may expect hundreds of lensed SMGs with magnification ~5-10

→ Unique legacy for mm/submm studies of molecular gas in high-z major starbursts (HLIRGs + ULIRGs even below the confusion limit)

- Effective sensitivity increase by ~10 for ALMA, IRAM/NOEMA etc. for studies of high-z ULIRGs/HLIRGs
- H_2O is an easy important tracer of compact, dense warm, strong-IR nuclei of SMGs, especially obscured AGN. It is complemented by various other molecular lines
- High-z HLIRGs have no local equivalent. Their unexplored cores should reveal extreme ISM conditions and outflows → clues for most massive galaxy formation
- New step in studying high-z lensing and their dark matter structures at higher deflector redshift up to z >~ 1
- But needs much follow-up and high-quality lensing modeling