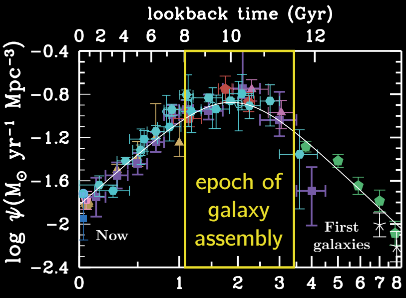
Physical conditions of the ISM in high-redshift lensed submillimeter galaxies

杨辰涛 (YANG, Chentao)

Collaborators: Alain Omont, Alexandre Beelen, Raphael Gavazzi, Yu Gao, Pierre Cox, Eduardo González-Alfonso, Roberto Neri & *Herschel*-ATLAS team

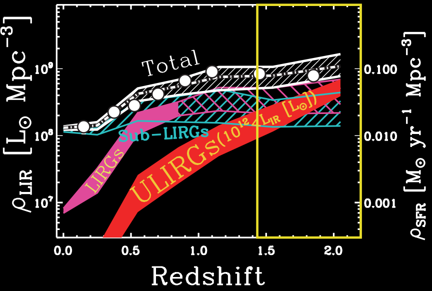
JAO, The ALMA Quest for Our Cosmic Origins, 27-March-2018.

The history of cosmic star formation



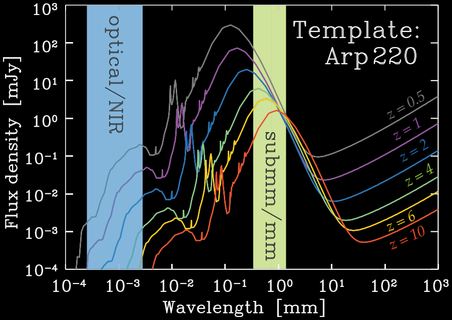
Madau & Dickinson 2014

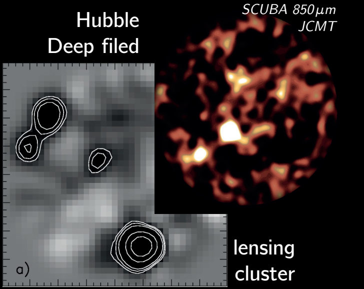
Magnelli et al. 2013



- Cosmic star formation history (CSFH) peaking around redshift ~2-3
- The galaxies gain most of their masses around this epoch.
- Infrared-luminous galaxies are crucial for studying the galaxy growth history, especially around the CSFH peak.

The discovery of submillimeter galaxies



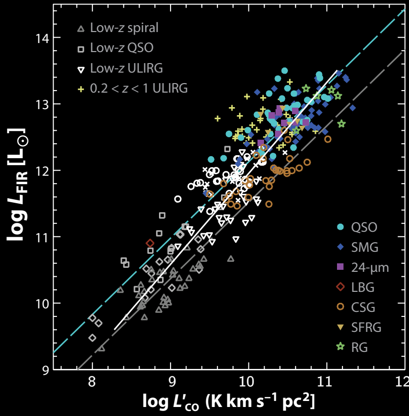


The first image of Submillimeter Galaxies (SMGs)
Smail et al. 1997 (also Hughes et al. 1998; Barger et al. 1998)

- Submillimeter galaxies (SMGs) usually having $L_{\rm IR} \gtrsim 10^{12} L_{\odot}$.
- The negative K-correction magically makes the detections easy to achieve.
- SMGs are believed to be the progenitors of today's most massive galaxies.
- What's the nature of SMGs (DSFG)? → Study their star formation. → Observing the ISM.

Why study the CO lines?

Carilli & Walter 2013

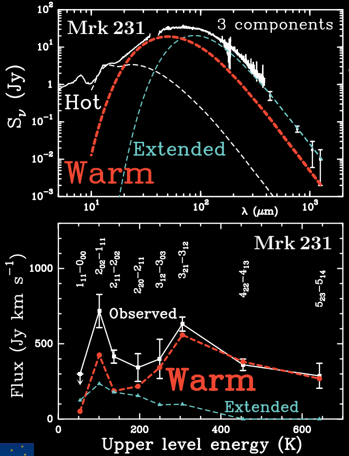


CO is the most important gas tracer:

- CO is the most abundant molecule after H_2, lines are the brightest
- Redshift search for dusty galaxies at high-z
- CO(1-0) traces the bulk of total molecular gas (H_2 mass, α_{CO})
- Kennicutt–Schmidt law: observationally, theoretically
- CO excitation: physical properties of the molecular gas
- Kinematics: rotation, merger, in/out-flow, etc.

The new powerful diagnostic tool: submm H_2O lines

e.g., in Arp220: *González-Alfonso et al. 2011*; APM08279: *van der Werf et al 2011; Lis et al 2011*



adapted from González-Alfonso et al. 2010

H_2O: **a powerful diagnostic tool :**

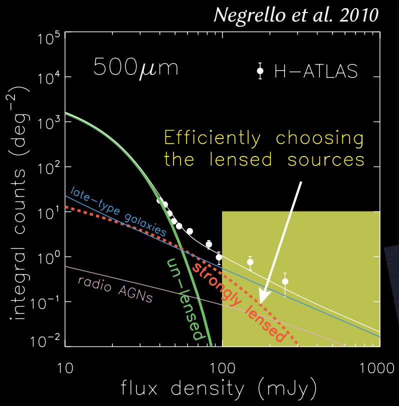
- A very different tracer from CO
- IR-pumping dominated ($J \geq 2$)
- High-J and low-J H_2O lines are comparable.
- Warm compact (far-IR-pumping) + cool extended (collision)
- Generally, H_2O lines diagnostic tells:
  - Molecular gas properties: e.g., column density of H_2O
  - FIR radiation field (dust) properties: e.g., T_{warm}, dust opacity, size, ...

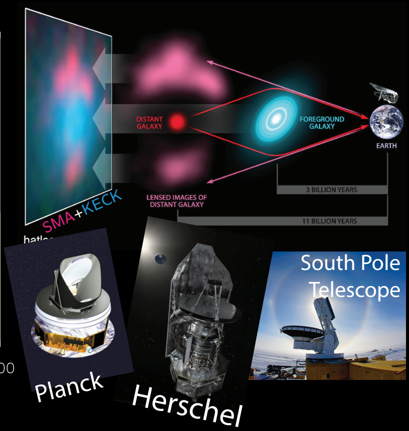
How to observe the submillimeter rotational H_2O lines?

- **In our Galaxy and in nearby galaxies:** very hard to observe from ground
  - Space telescopes: e.g., *Odin*, *SWAS* , *ISO*, *Spitzer*, *Herschel*

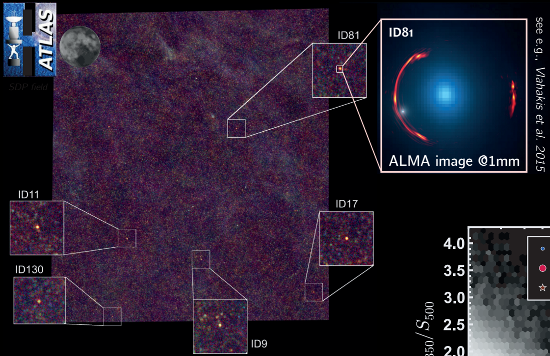
- **In high-redshift galaxies**: shifted into atmospheric windows, but very weak
  - **Extremely powerful** telescope with a lot of integration time!
  - With moderate observing time, through **gravitational lensing**: picking up sources from lensing surveys: e.g., *Herschel*-ATLAS, SPT and *Planck* all-sky surveys.

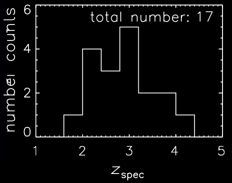
Finding the strongly lensed SMGs via submm surveys





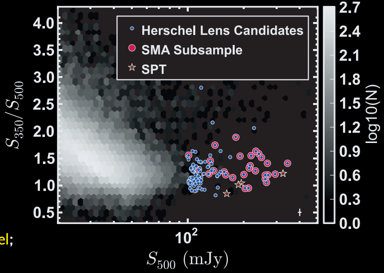
Strongly lensed SMGs discovered by *Herschel*-ATLAS



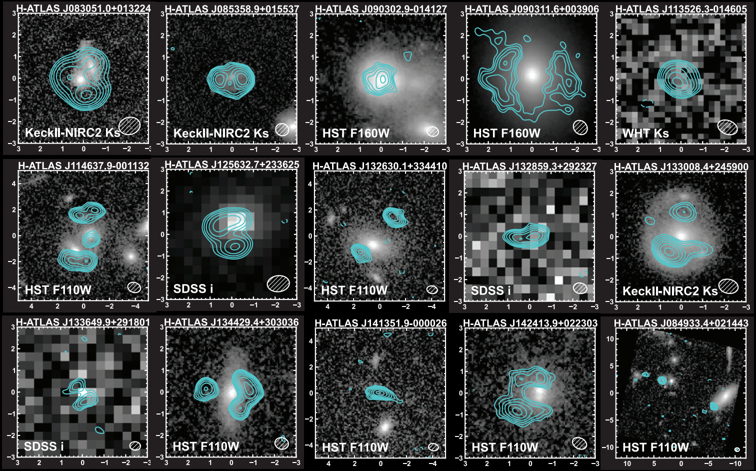


Herschel-ATLAS (570 deg^2, *Eales et al. 2010*):

- Covering 5 bands from 100 µm to 500 µm;
- Selecting strongly lensed candidates by $S_{500\,\mu m}$>100 mJy;
- Determining the redshifts by follow-up CO observations;
- Follow-up imaging observations for building lensing model; (Sample with ~30 sources, *Bussmann et al. 2013*)



Optical and submm images of the sample

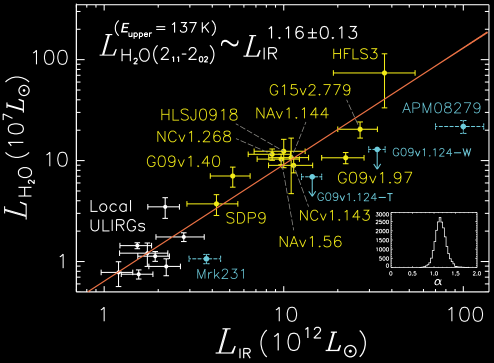


+ two sources with CO(1-0) detection lacking submm image

(*Bussmann et al 2013; Harris et al 2012*)

L_{H_2O} vs L_{IR} from local ULIRGs to the high-redshift SMGs

21/23 in 17 SMGs, largest high-z H_2O study: *Omont, Yang et al. 2013; Yang et al. 2016*



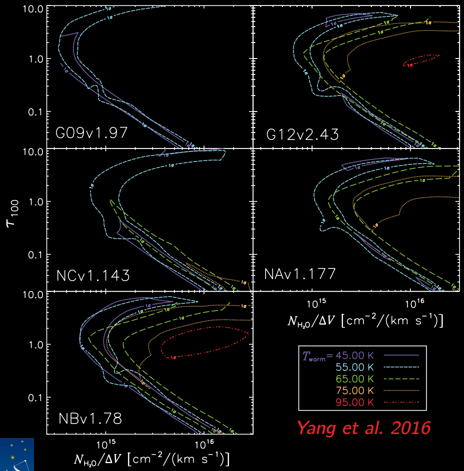
$L^{(E_{upper}=101\,K)}_{H_2O(2_{02}-1_{11})} \sim L_{IR}^{1.06\pm0.19}$

$L^{(E_{upper}=305\,K)}_{H_2O(3_{21}-3_{12})} \sim L_{IR}^{1.06\pm0.22}$

- $L_{IR} \propto L_{H_2O}$ can be explained by the IR-pumping model
- The H_2O lines are good tracer of the IR radiation sources that connect to star formation (no mid-IR/radio AGN signature)

Modelling the H_2O line excitation in high-*z* SMGs

Pure IR-pumping H_2O excitation model of *González-Alfonso et al. 2014*



Yang et al. 2016

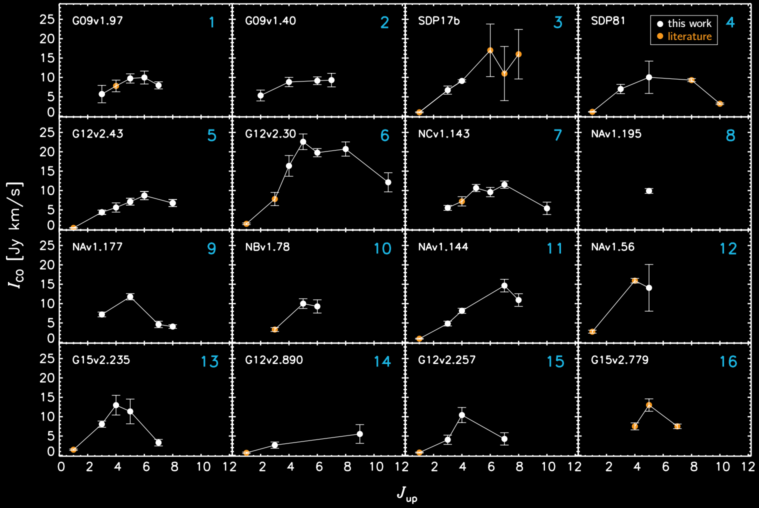
In 5 of the sources, we have both $J = 2$ & $J = 3$ H_2O detections:

- Assuming pure H_2O IR-pumping model;
- The H_2O column density is similar to local infrared galaxies;
- The H_2O line excitation is mainly powered by dust with temperature around 45–75 K;
- Strong degeneracies: $J \geq 4$ H_2O lines are needed for better constraints of the model.

Going back to the standard gas tracer: A large sample of multiple-J CO study in $z \sim 2$–4 SMGs

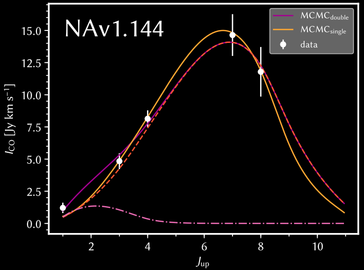
IRAM-30m observations of multi-J CO lines

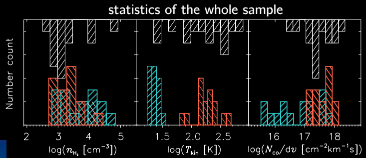
Newly detected 47 multiple-J CO and 7 CI lines in 15 SMGs. *Yang et al. 2017*

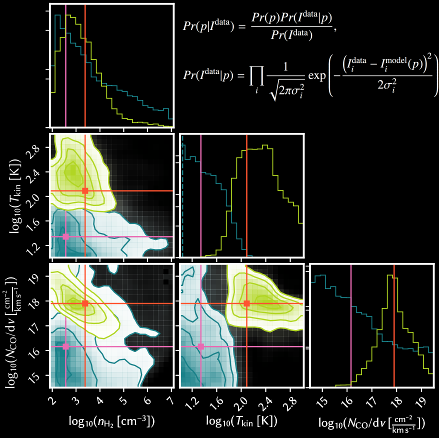


Radiative transfer modelling of the CO line excitations

RADEX (non-LTE) + `emcee` (MCMC with affine-invariant ensemble sampler) –a better flux recovery of the low-J CO lines from two-components fitting







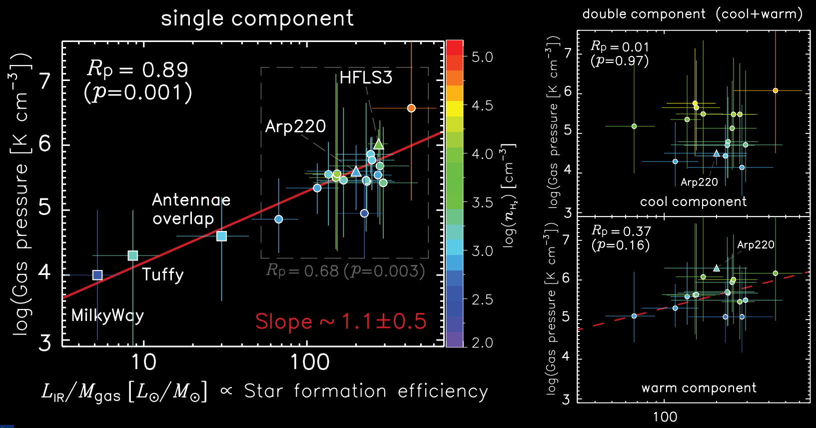
$$Pr(p|I^{\rm data}) = \frac{Pr(p)Pr(I^{\rm data}|p)}{Pr(I^{\rm data})},$$

$$Pr(I^{\rm data}|p) = \prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{\left(I_i^{\rm data} - I_i^{\rm model}(p)\right)^2}{2\sigma_i^2}\right),$$

cyang@eso.org

What is regulating the star formation efficiency, pressure?

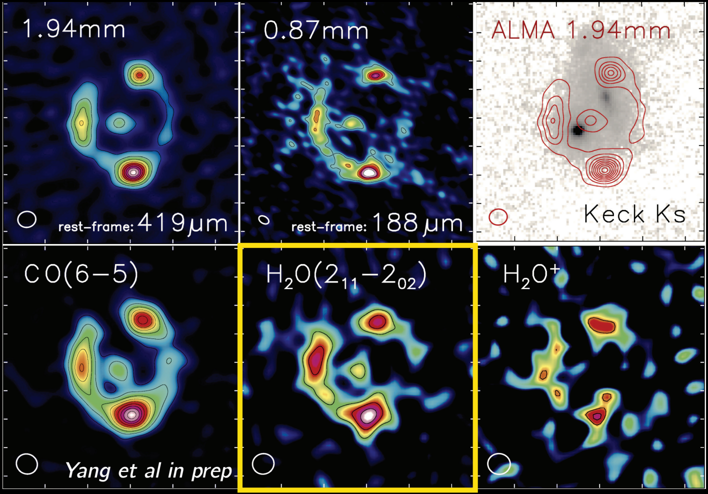
A way to understand the variation seen in the star formation law?



Next step: From unresolved observations to high angular-resolution images of the molecular gas in strongly lensed SMGs

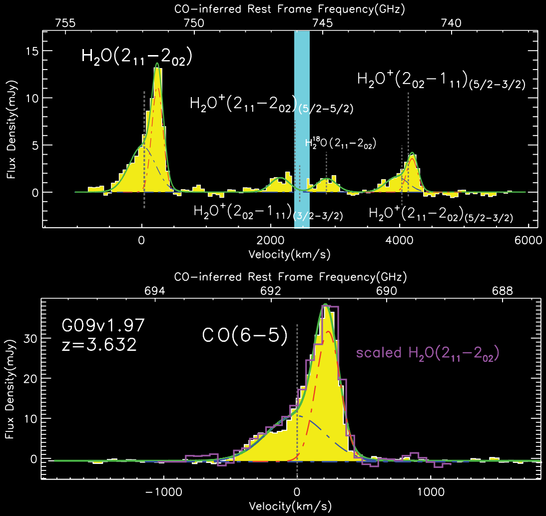
ALMA 0.″4 images of H_2O, CO and dust continuum

The highest angular-resolution H_2O image (~3 kpc) at any redshift



ALMA integrated spectra of H_2O, CO and dust

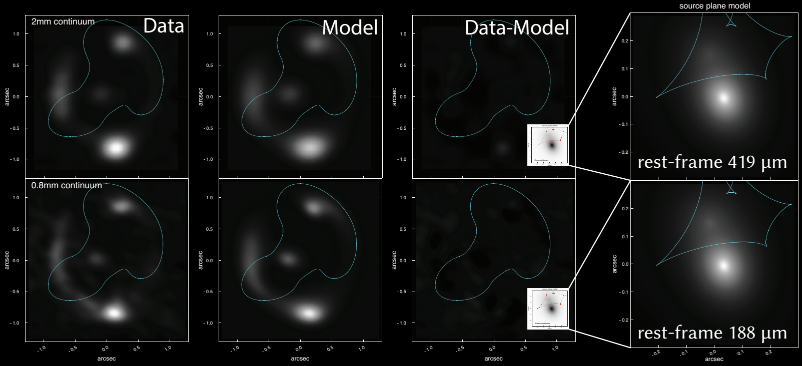
Yang, Gavazzi, et al., in prep.



Lens modelling: MCMC using the CLEANed images

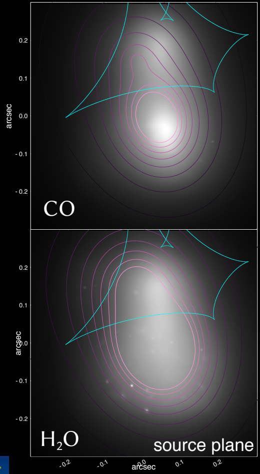
Yang, Gavazzi, et al., in prep.

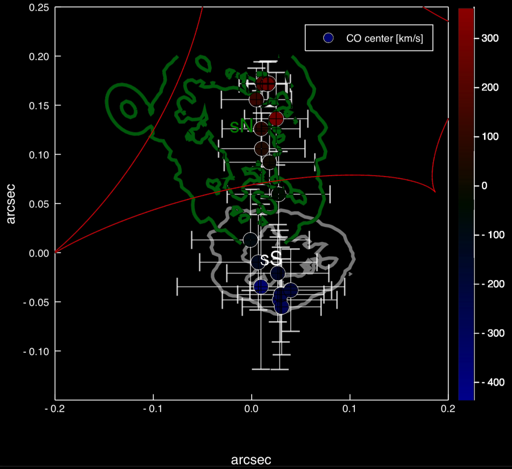
Parameters of SIE mass components	x_{def} arcsec	y_{def} arcsec	q_{def}	PA_{def} deg	σ km s^{-1}
South-East $z = 0.626$ lens	-0.28 ± 0.03	-0.11 ± 0.03	0.49 ± 0.09	118 ± 7	143 ± 6
North-West $z = 1.002$ lens	0.14 ± 0.03	0.42 ± 0.04	0.73 ± 0.10	30 ± 10	181 ± 5



Source plane image of dust, CO and H_2O

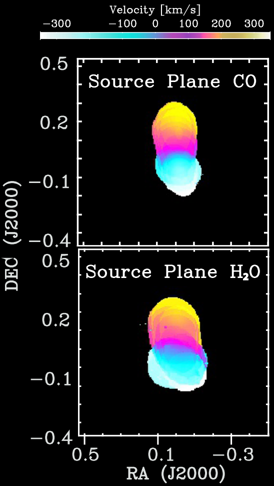
Yang, Gavazzi, et al., in prep.

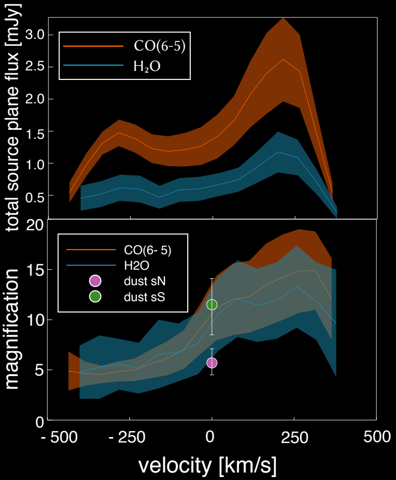




Strikingly similar velocity strucutre between H_2O and CO

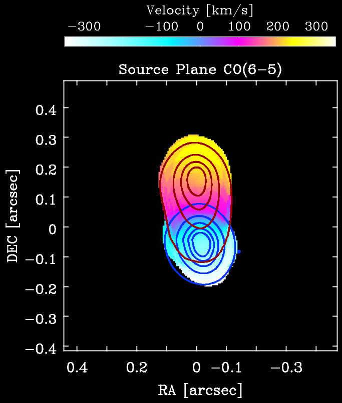
Instrinsic properties of the molecular line emission. *Yang, Gavazzi, et al., in prep.*

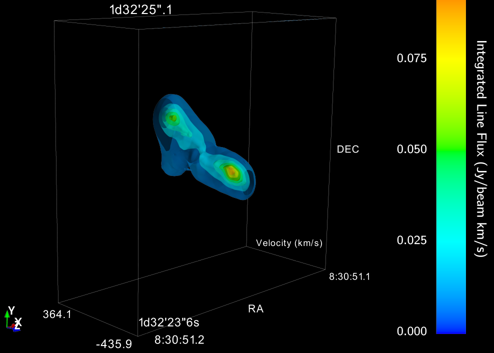




Kinematic structure - a close merging pair

Extended red + compact blue. *Yang, Gavazzi, et al., in prep.*





Summary

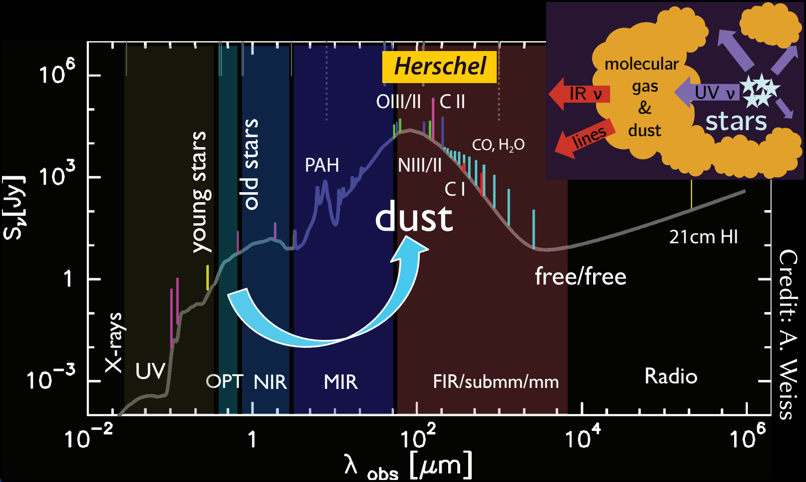
Largest sample study of submm H_2O line and multiple-J CO line (CO SLED) study in high-redshift SMGs –

- H_2O is a powerful diagnostic tool for the infrared sources in the warm, dense regions linked to intense star formation. The lines are bright.
- $L_{H_2O} \sim L_{IR}^{1.1-1.2}$, correlating strongly with star formation.
- IR pumping plays an important role in the submm H_2O excitation and dominates the $J \geq 2$ H_2O excitation.
- Mid/high-J CO lines also tightly correlated with FIR luminosity.
- Gas pressure plays an important role in regulating star formation.
- Mid/high-J CO and similar spatial distribution and velocity structure as H_2O. Both located similarly as the warm dust continuum.
- Our *Herschel*-ATLAS lensed SMGs have similar properties as other SMGs samples around z~2-4.

Thank you for your attention!
Questions?

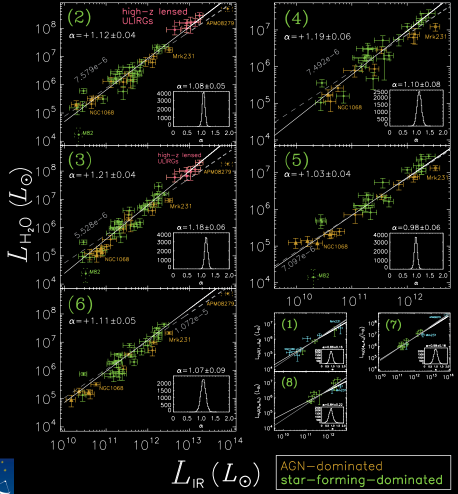
Chentao Yang, 27-Mar-2018

How do we study a dusty (infrared) galaxy?



A first systematic study of H_2O in local infrared galaxies

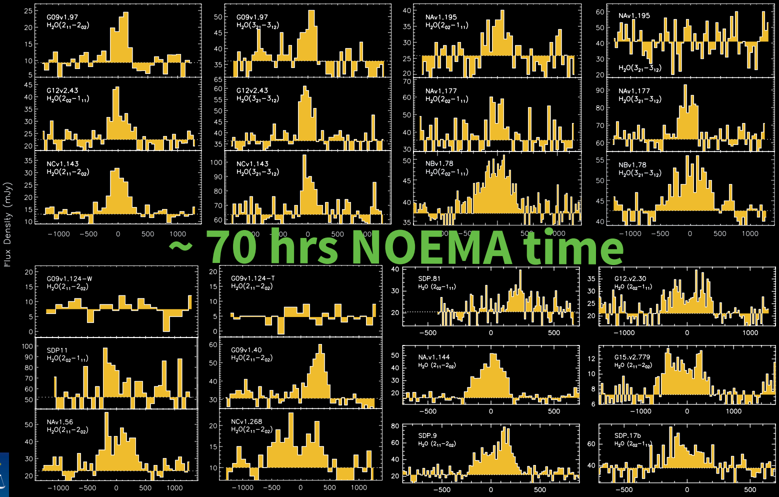
Yang et al., 2013



- **First/largest systematic** study of submm rotational H_2O emission lines in local galaxies; (Thanks to *Herschel* SPIRE/FTS!)
- The H_2O lines are among the **strongest** molecular lines, comparable with high-J CO, **flux ratio of H_2O/CO ~ 0.3 to 1**;
- **Tight correlation of $L_{H_2O} \propto L_{IR}$**: confirming the importance of IR-pumping.

H_2O detections in the *Herschel* high-*z* lensed SMGs

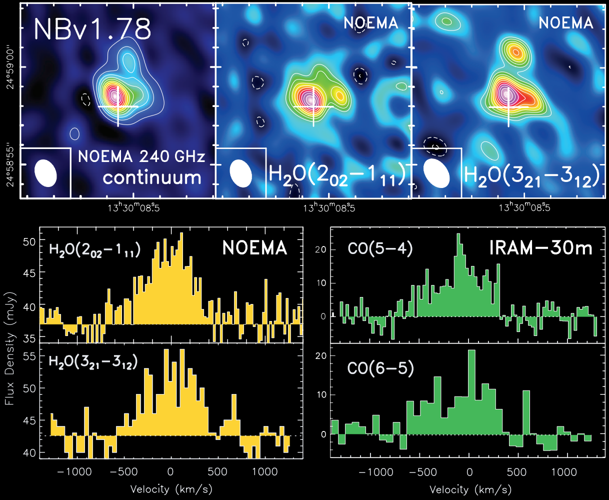
21/23 in 17 SMGs, largest high-*z* H_2O study: *Omont, Yang et al. 2013; Yang et al. 2016*



~ 70 hrs NOEMA time

H_2O lines of high-redshift lensed SMGs (an example)

21/23 in 17 SMGs, 5 sources with both J=2 & J=3 H_2O, *Yang et al., 2016*

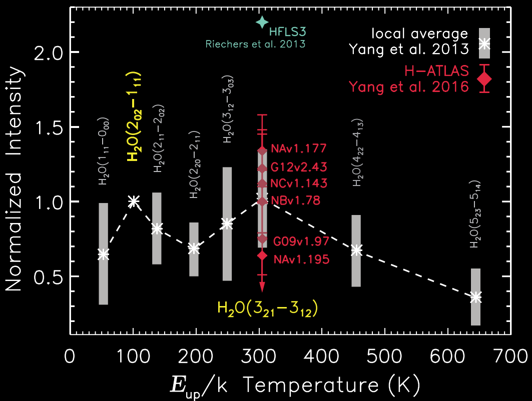


H_2O Spectral Line Energy Distribution (SLED)

Exploring the H_2O excitation in *Herschel* high-redshift SMGs, *Yang et al., 2016*

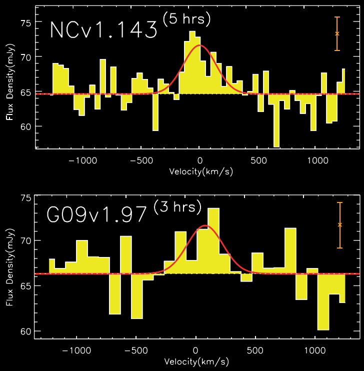
H_2O SLED normalized by 2_{02}-1_{11} intensity:

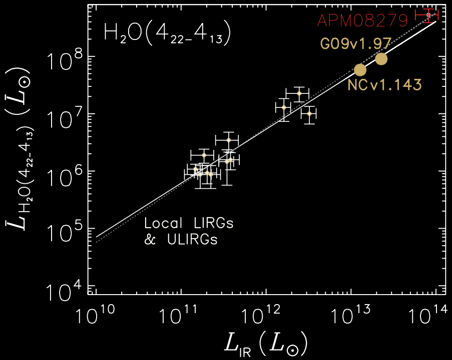
- The ratio between $H_2O(3_{21}$-$3_{12})$ and $H_2O(2_{02}$-$1_{11})$ are within local range.
- Different flux ratios of line $H_2O(3_{21}$-$3_{12})$ over $H_2O(2_{02}$-$1_{11})$.
- Indicating various properties of infrared radiation fields.



Observing the $J = 4$ H_2O lines using NOEMA/IRAM

Yang et al, in prep: $L_{\rm IR}$-$L_{\rm H_2O(4_{22}-4_{13})}$ correlation and the H_2O line excitation modeling

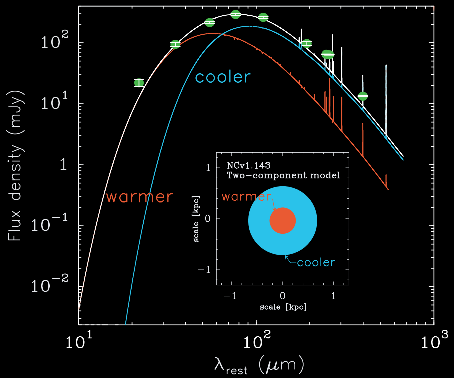




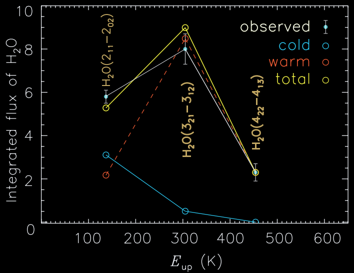
- The detections following the similar scaling relation found in local (U)LIRGs

H_2O excitation modelling

Yang et al, in prep: Using the H_2O excitation model of *González-Alfonso et al. 2014*



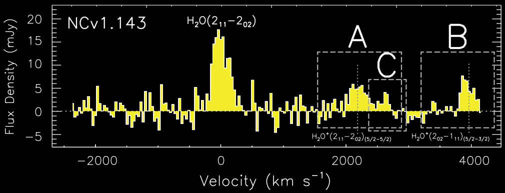
- Cold: 35 K, 700pc, N_{H_2O} ~ 5×10^{18} cm^{-2} km^{-1} s
- Warm: 75 K, 230pc, N_{H_2O} ~ 2×10^{19} cm^{-2} km^{-1} s

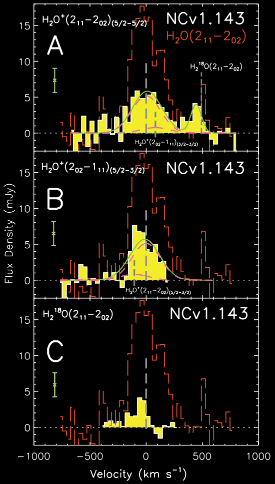


- Two components (warm + cold) are needed for the H_2O line modelling;
- ALMA will increase the sample size significantly!

$H_2O^+/H_2^{18}O$ emission is detected in high-redshift SMGs

Yang et al. 2016: **shedding light on the oxygen chemistry**



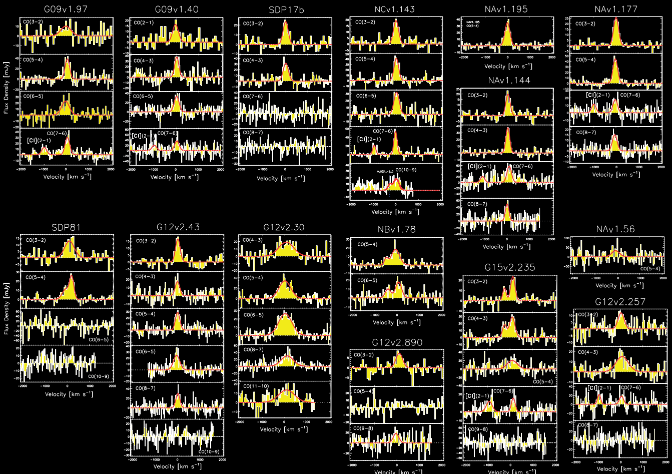


- J=2 H_2O^+ lines can be observed along with H_2O;
- J=2 H_2O^+ lines are bright;
- Similar line profiles between J=2 H_2O & H_2O^+;
- H_2O^+/H_2O flux ratio ~ 0.3: cosmic rays may drive the oxygen chemistry (taking PDR+cosmic-ray model from *Meijerink et al. 2011*);

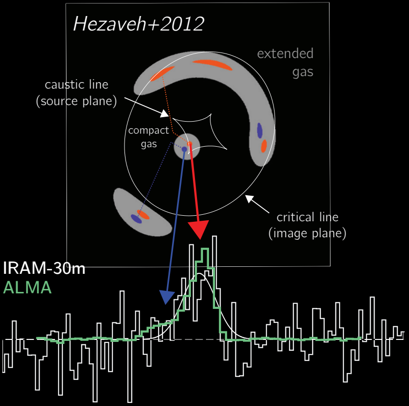
cyang@eso.org

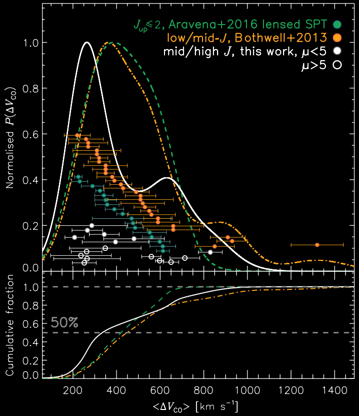
IRAM-30m spectra of the CO and [CI] lines

[CI](2-1) can be detected together with CO(7-6). *Yang et al. 2017*

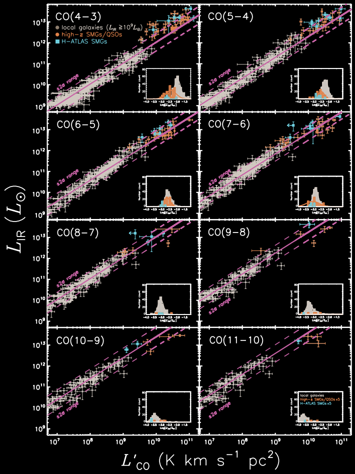


Differential lensing: linewidth under-estimation



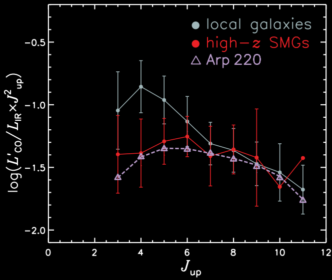


Molecular gas in the SMGs as probed by multi-J CO lines



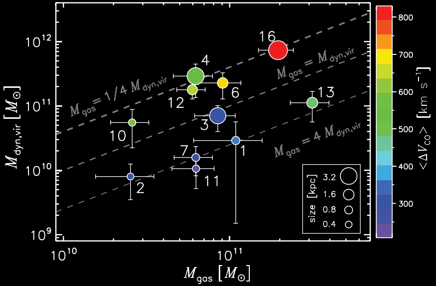
Largest sample of multi-J CO in high-z lensed SMGs *(Yang et al. 2017)*

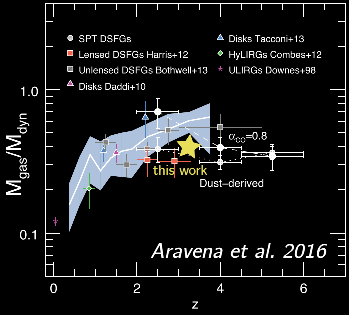
- L_{CO}-L_{IR} Correlation:
  - Mid/high-J CO following *Liu et al. 2015*
  - Like other high-z SMGs
  - the SMGs are like local ULIRGs
- At least two excitation components are needed.



Dynamics and molecular gas mass fraction

$$M_{\rm dyn,vir} = 1.56 \times 10^6 \left(\frac{\sigma}{\rm km\,s^{-1}}\right)^2 \left(\frac{r}{\rm kpc}\right) M_\odot,$$

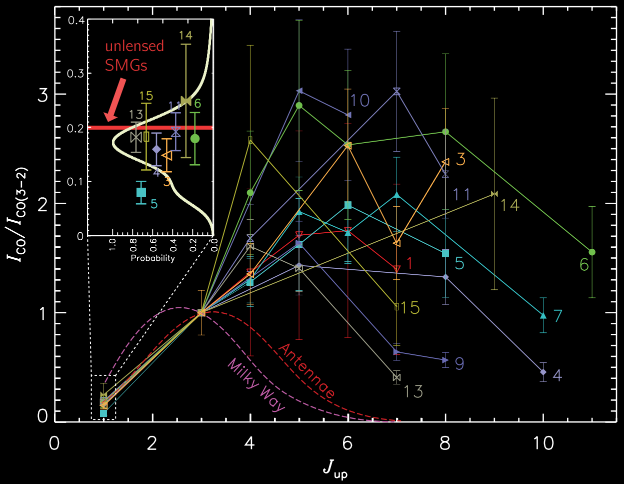




- Further evidence of linewidth underestimation.
- For the sources with little differential lensing: molecular gas mass fraction $\sim 34\%$, agrees with model and other SMGs ($M_{\rm dyn}$ is very uncertainy though).

Correcting for differential lensing for the extended gas

Yang et al. 2017



Star formation in high-redshift SMGs

$M_{H_2} = \alpha_{CO} L'_{CO(1-0)}$, $t_{dep} \equiv M_{gas}/SFR$, $\delta_{GDR} = M_{gas}/M_{dust}$ $\delta_{GDR}/\alpha_{CO} = L'_{CO(1-0)}/M_{dust}$,