Molecular gas in high-redshift strongly lensed dusty starbursts as traced by multiple-J CO lines

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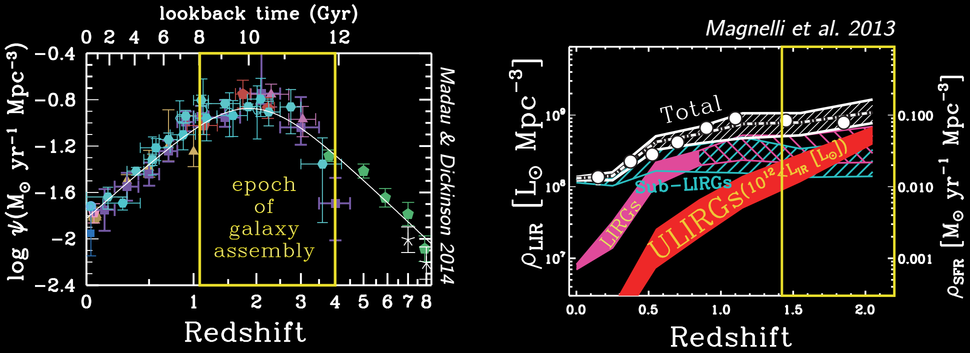
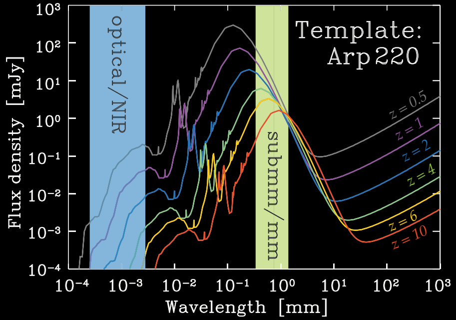
The Laws of Star Formation, @University of Cambridge, 06-July-2018.

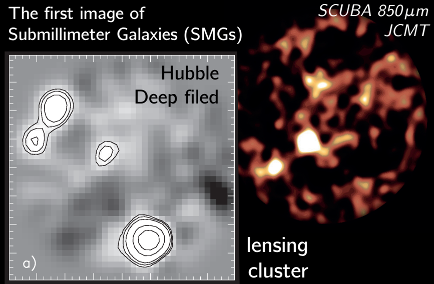
Understanding how galaxies grow, the cosmic star formation history



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

IR-luminous objects at high-redshift: submillimeter galaxies (SMGs)



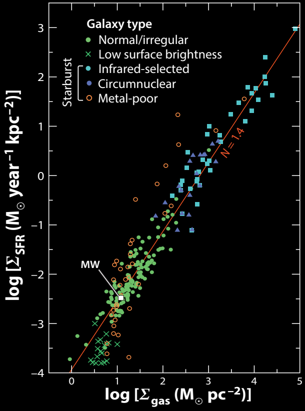


Smail et al. 1997 (also Hughes et al. 1998; Barger et al. 1998)

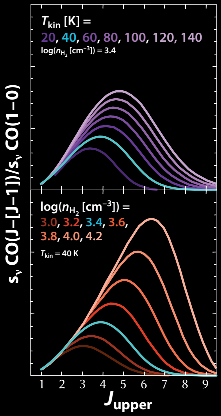
- **Submillimeter galaxies (SMGs)** usually having $L_{\rm IR} \gtrsim 10^{12} L_{\odot}$, "star-forming monsters".
- The negative K-correction magically makes the detections easy to achieve.
- SMGs are believed to be the progenitors of today's most massive galaxies.
- What's the nature of SMGs (DSFG)?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

How do we study the ISM properties? - The multiple-J CO lines help.

Kennicutt & Evans 2012



Carilli & Walter 2013



CO is the most important gas tracer:

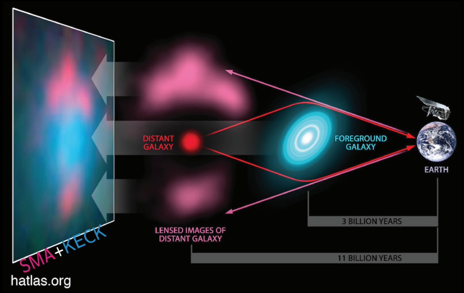
- CO is the most abundant molecule after H_2, lines are the brightest
- Redshift search for dusty galaxies at high-redshift
- CO(1-0) traces the bulk of total molecular gas (H_2 mass, α_{CO})
  - Kennicutt–Schmidt law: observationally, theoretically
- CO excitation: physical properties of the molecular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

How to observe the multiple-J CO lines (submm regime)?

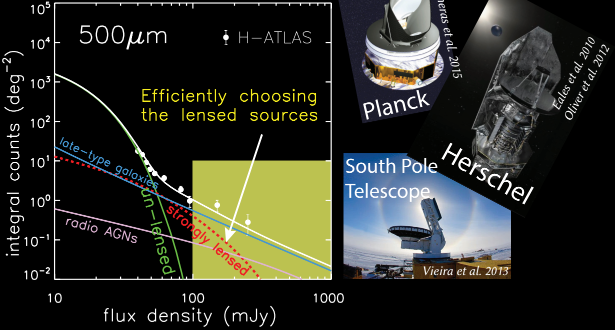
- **In high-redshift galaxies**: shifted into atmospheric windows, but very weak

- **Extremely powerful** telescope with a lot of integration time!
- With moderate observing time, through **gravitational lensing**, "Cosmic telescope" : boosted apparent flux and spatial resolution.

How to find strongly lensed SMGs? –Via submm surveys

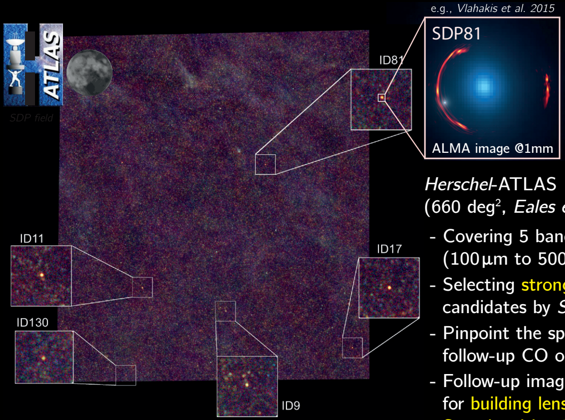


Blain 1996; Negrello et al. 2007, 2010
see also Wardlow et al. 2013



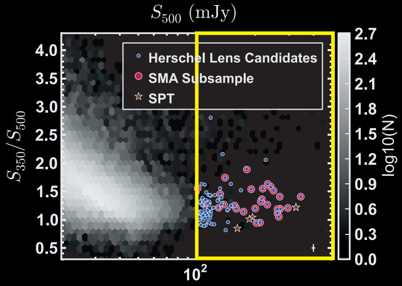
- Picking up strongly lensed candidates by a simple flux cut.
- Need large area surveys at submm.

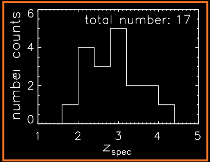
Strongly lensed SMGs discovered by *Herschel*-ATLAS



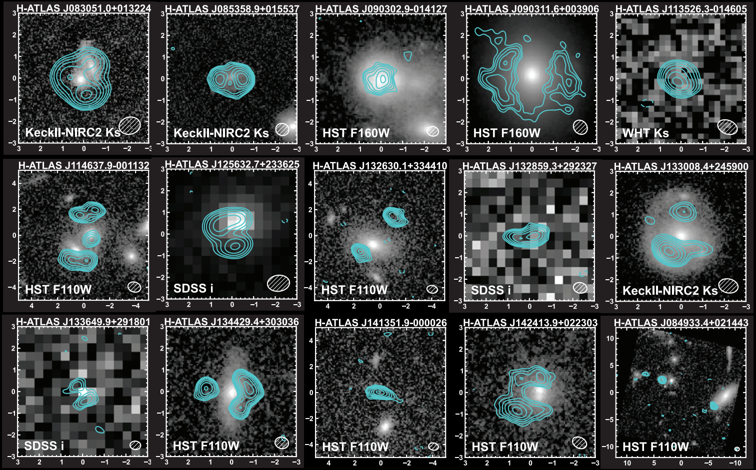
Herschel-ATLAS
(660 deg[2], *Eales et al. 2010*):

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





Optical (foreground) and submm (background) images of the sample

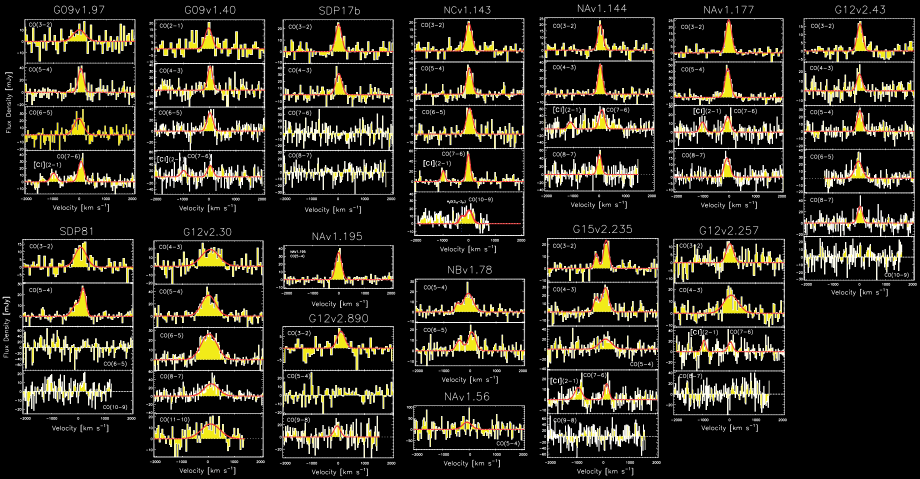


(Bussmann et al 2013; Harris et al 2012)

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

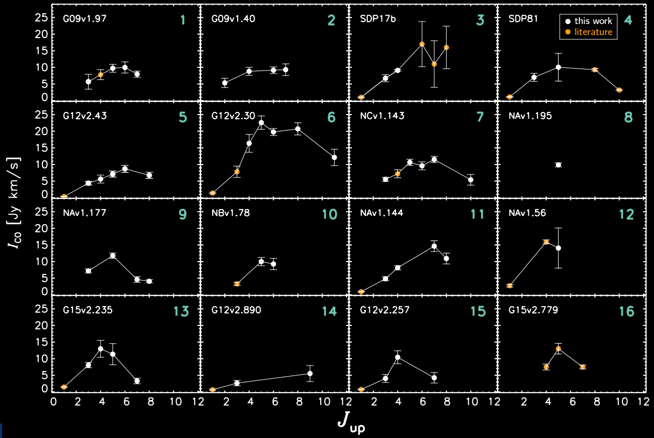
IRAM-30m spectra of the CO and [CI] lines of the lensed SMGs

PI projects, ~100 hours IRAM-30m, *47 CO lines in total.* *(Yang et al. 2017)*



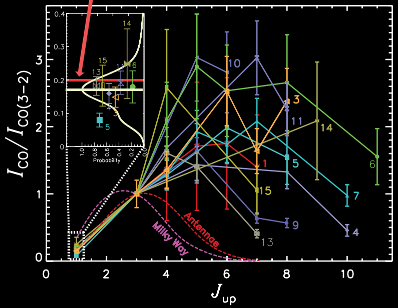
CO SLEDs (ladders) of the lensed SMG sample

More than 50 multiple-J CO and 7 CI lines in 16 SMGs. *Yang et al. 2017*

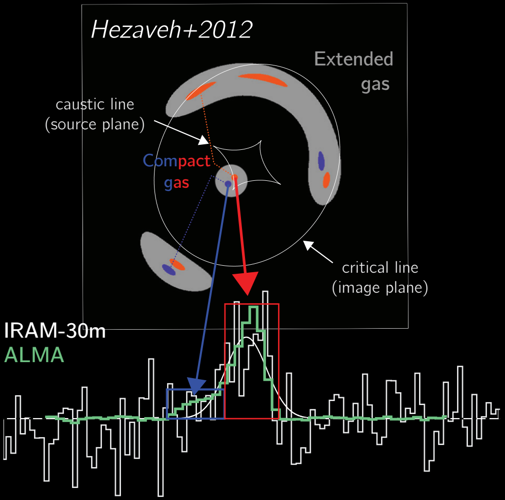


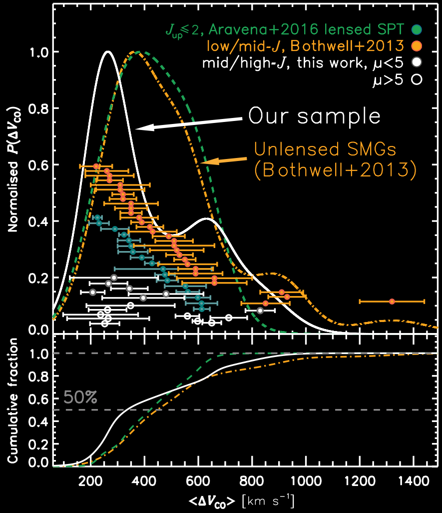
Low CO(1-0)/CO(3-2) compared with unlensed SMG samples
- Differential lensing!
- CO(1-0) is more extended (*Ivison+2011*).

Bothwell+2013, unlensed SMGs



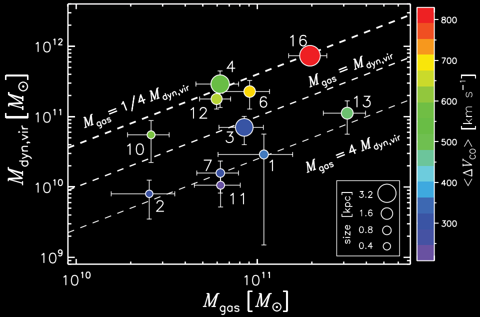
Differential lensing could cause underestimation of linewidth

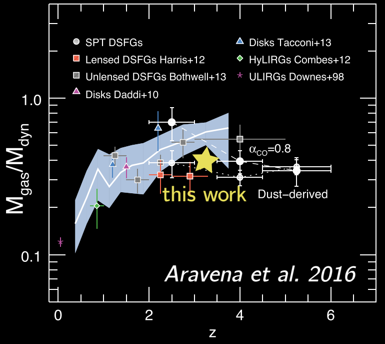




Dynamics and molecular gas mass fraction

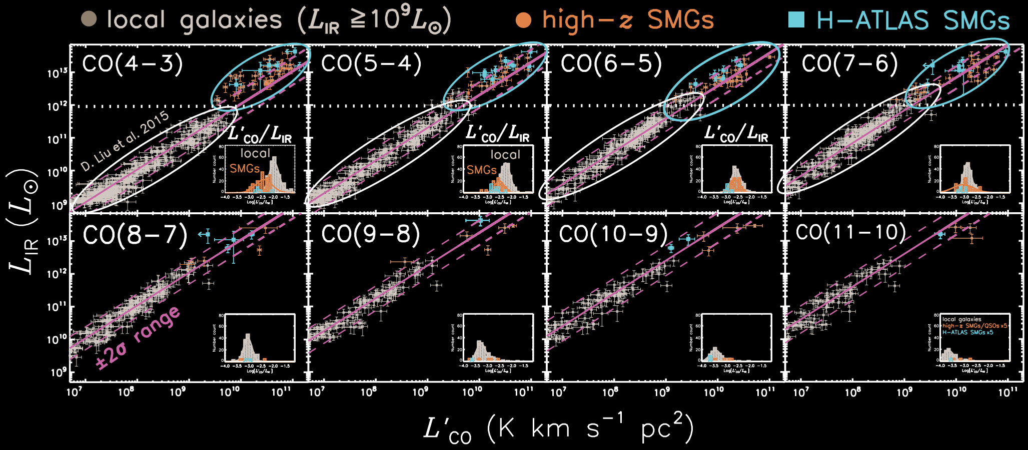
$$M_{\rm dyn,vir} = 1.56 \times 10^6 (\frac{\sigma}{\rm km\,s^{-1}})^2 (\frac{r}{\rm kpc})\, M_\odot,$$



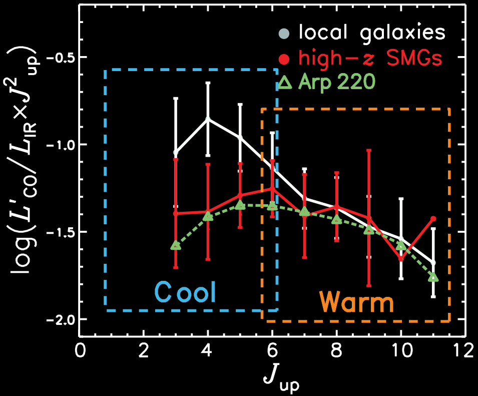


- Further evidence of linewidth underestimation.
- For the sources with little differential lensing: molecular gas mass fraction ~ 34%, agrees with model and other SMGs ($M_{\rm dyn}$ is very uncertainty though).

L-L correlation the CO lines, compared with other star-forming galaxies



L_{IR}-normalized CO SLEDs, multiple gas-excitation components



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

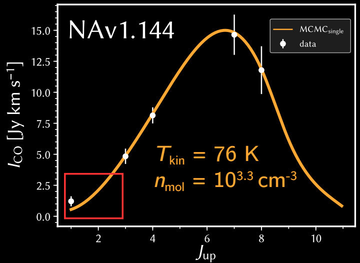
- L_{CO}-L_{IR} Correlation:
  - Mid/high-J CO following (*Liu et al. 2015*)
  - Similar to other SMG sample
  - Similar excitation condition in local SF ULIRGs
- A single gas excitation component is not enough
  - At least two components are needed.
- CO ladders of SMGs are similar to local ULIRGs
  - Similar gas excitation condition

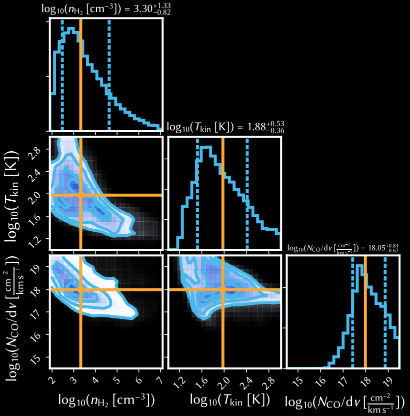
(Evidence of multiple excitation components: see also e.g. *Daddi+2015*, *Cañameras+submitted*)

Radiative transfer modeling of the CO line excitations

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

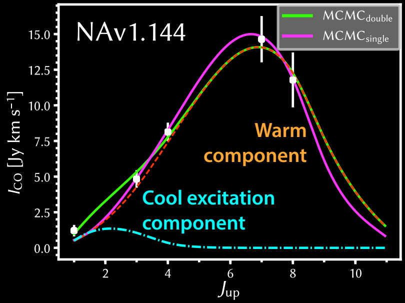
$$Pr(I^{\rm data}|p) = \prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{\left(I_i^{\rm data} - I_i^{\rm model}(p)\right)^2}{2\sigma_i^2}\right),$$

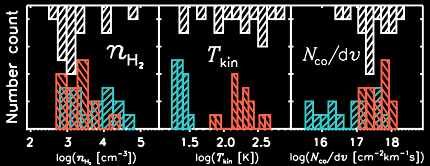




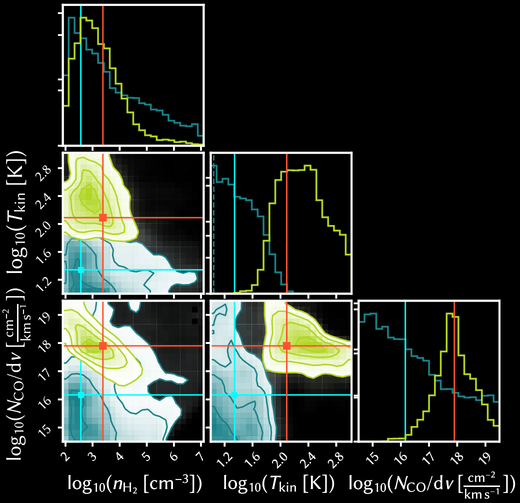
- RADEX (*van der Tak et al. 2007*) + emcee (*Foreman-Mackey et al. 2013*), LVG+MCMC `https://github.com/yangcht/radex_emcee`
- Informative priors based on physical constraints.

Radiative transfer modeling of the CO line excitations



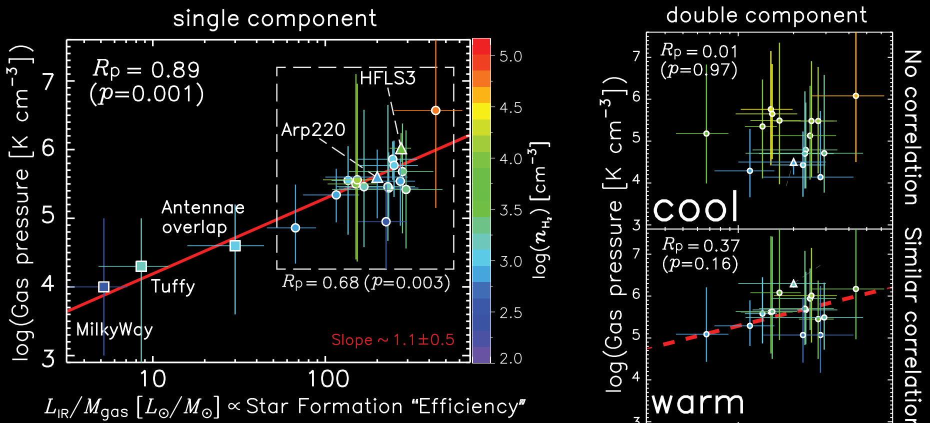


Statistics of the whole sample



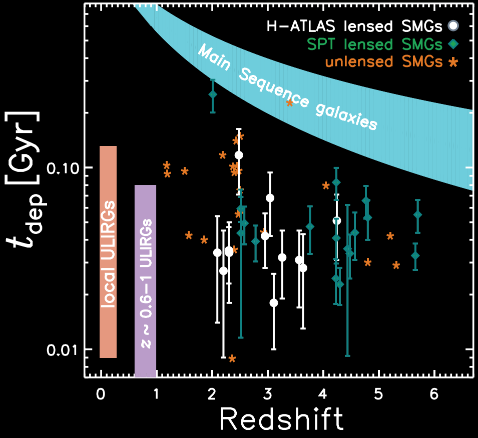
Star formation efficiency correlates with gas thermal pressure

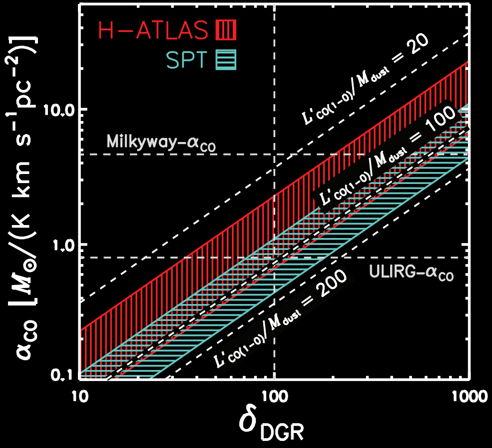
A way to understand the variation seen in the star formation law?



Depletion time scale and the conversion factor

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





Main conclusions

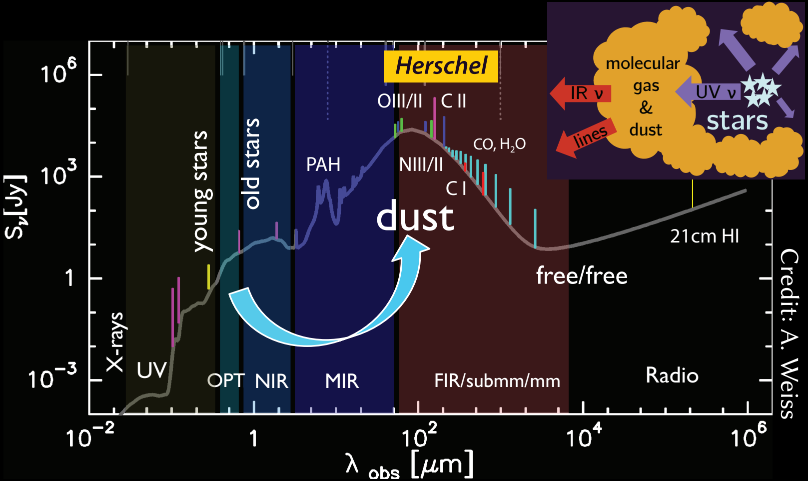
Large sample study of multiple-J CO line (CO SLED) study in high-redshift SMGs –

- Differential lensing causes underestimation of linewidth, hence dynamical masses.
- A change of the CO–IR correlation with excitation levels. SMGs/ULIRGs are different compared with normal SFGs.
- At least two gas excitation components are in SMGs. The CO SLEDs are very similar to the ones of local star-forming dominated ULIRGs (Arp220).
- Gas thermal pressure correlates with SFR/M_{gas}, Star Formation Efficiency.
  - The warm component is tightly linked to star formation, but not the cold one.
- Our *Herschel*-ATLAS lensed SMGs have similar properties as other SMGs samples around z~2—4.

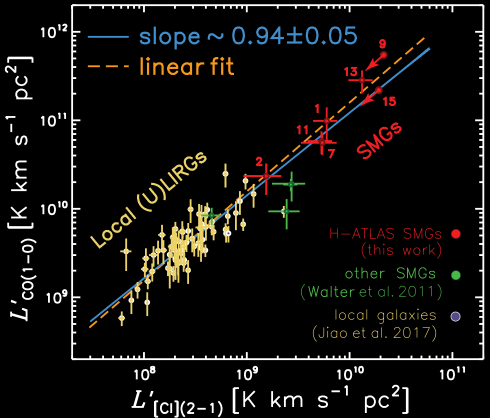
Thank you for your attention!
Questions?

Chentao Yang, 06-July-2018

How do we study a dusty (infrared) galaxy?



Another total molecular gas tracer: atomic carbon lines



CI is an alternative total molecular gas tracer:

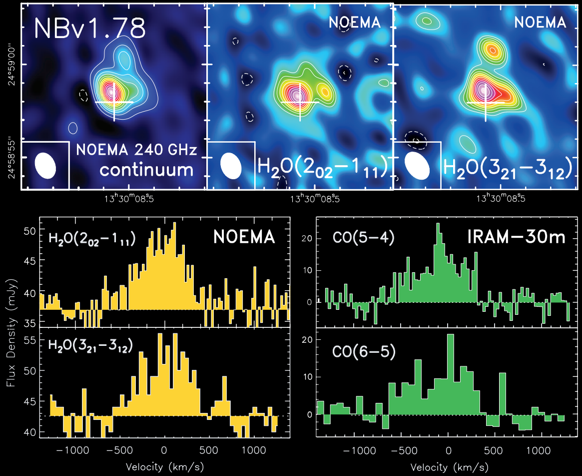
- CI is a simple three-level system, easily excited
- Molecular gas properties can be accurately derived
- Cosmic-ray chemistry may influence CO abundance.
- CI lines are in good observational windows

CI line in high-redshift SMGs:

- Following similar linear correlation found in local (U)LIRGs

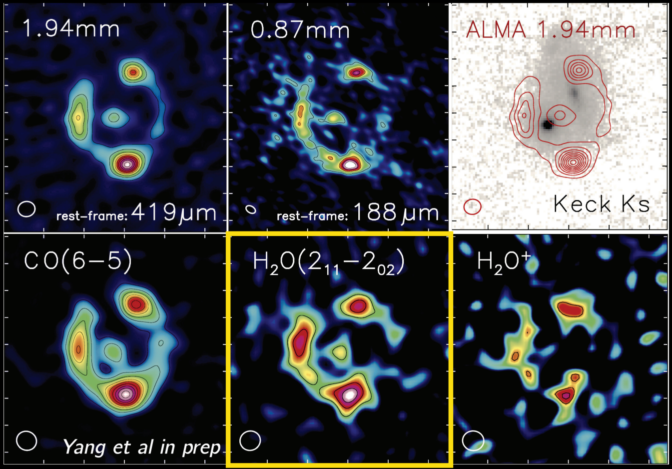
H_2O lines of high-redshift lensed SMGs (an example)

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



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., to be submitted