Molecular Gas at Cosmic Dawn

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AAS Cosmic Dawn SIG

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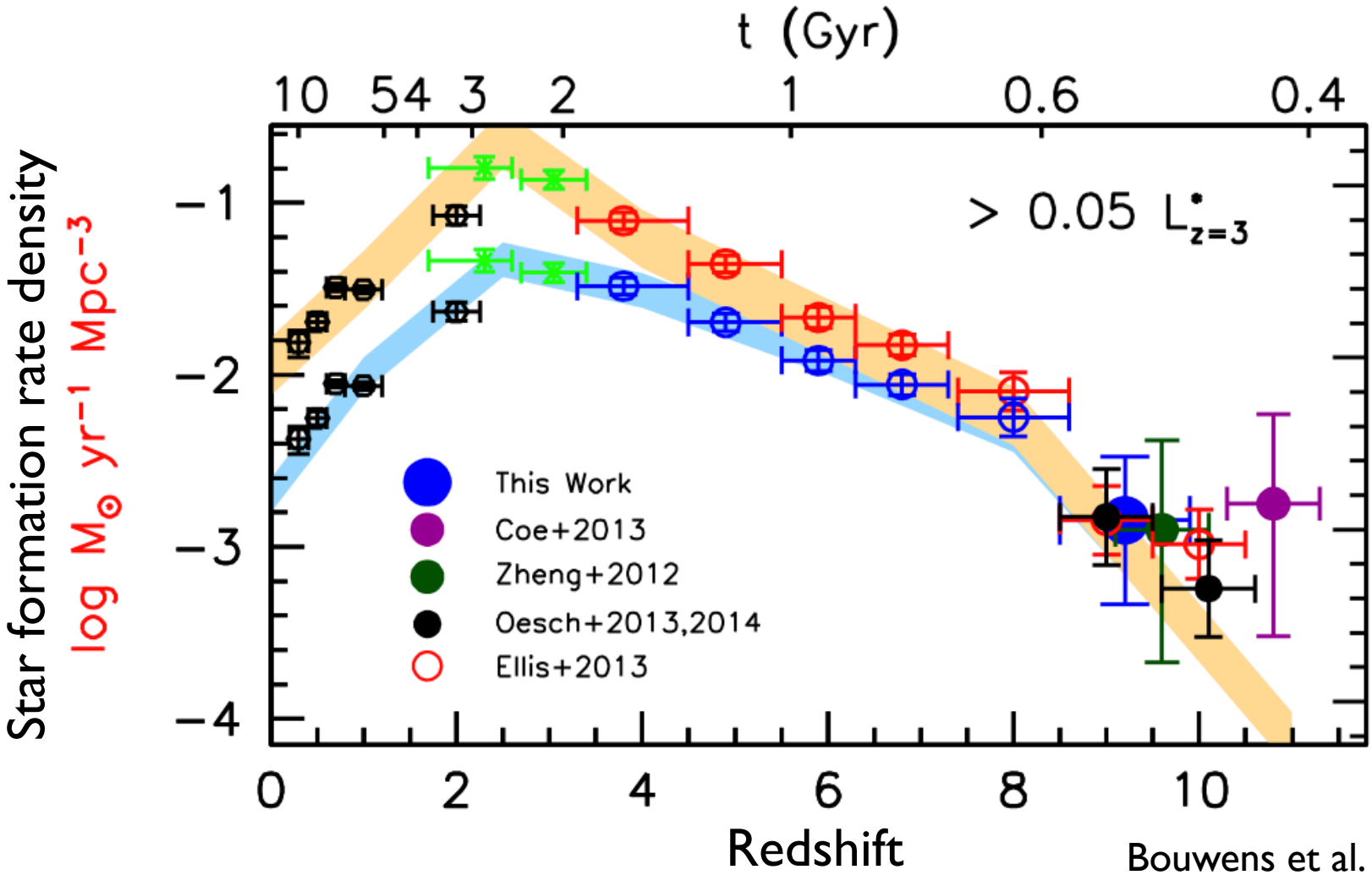
Overview

- Background
  - Why we care about molecular gas at high-z
  - Status and near-future observational prospects
- Ground+Space synergies
- The future of molecular gas observations

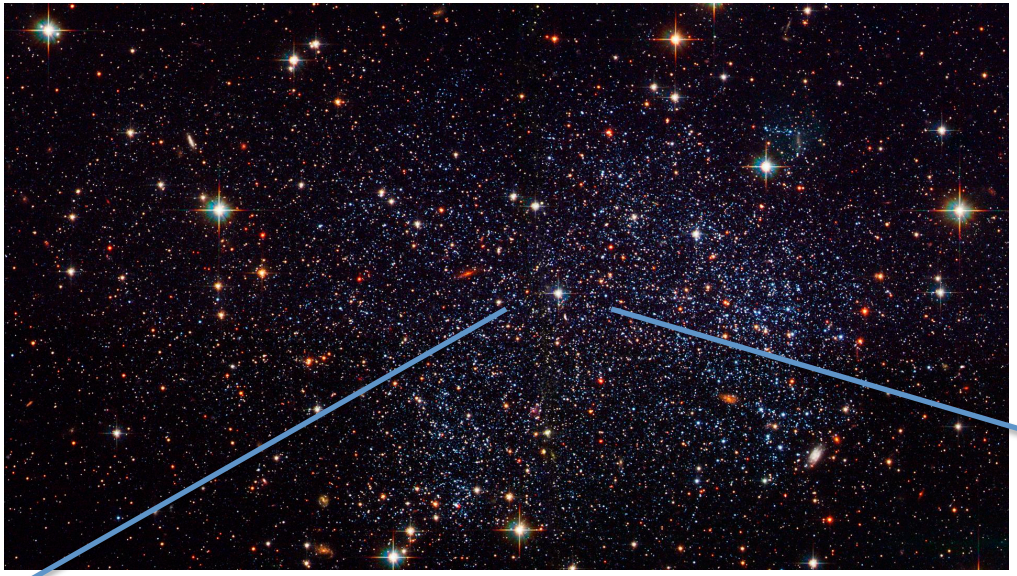
Hubble Deep Field

Star Formation History of the Universe



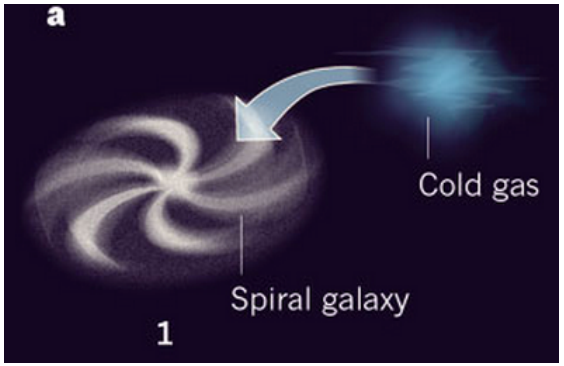
Bouwens et al. (2014)

The gas-star formation connection

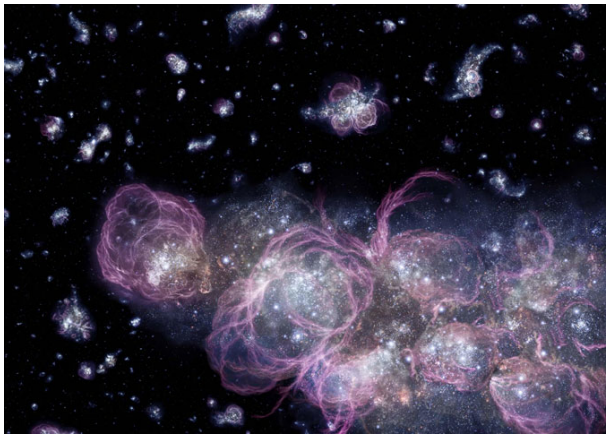


Much theoretical progress: E.g., Schaye et al. 2010, 2015; Booth & Schaye 2010; Dave et al. 2012; Haas et al. 2013; Feldmann 2013; Dekel et al. 2013; Altay et al. 2013; Lily et al. 2013; Sanchez Almeida et al. 2014; Furlong et al. 2014, etc …

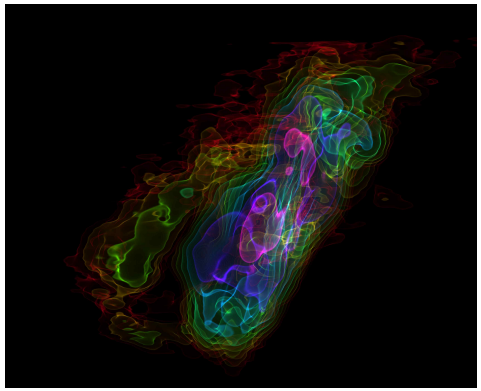
- Gas accretion



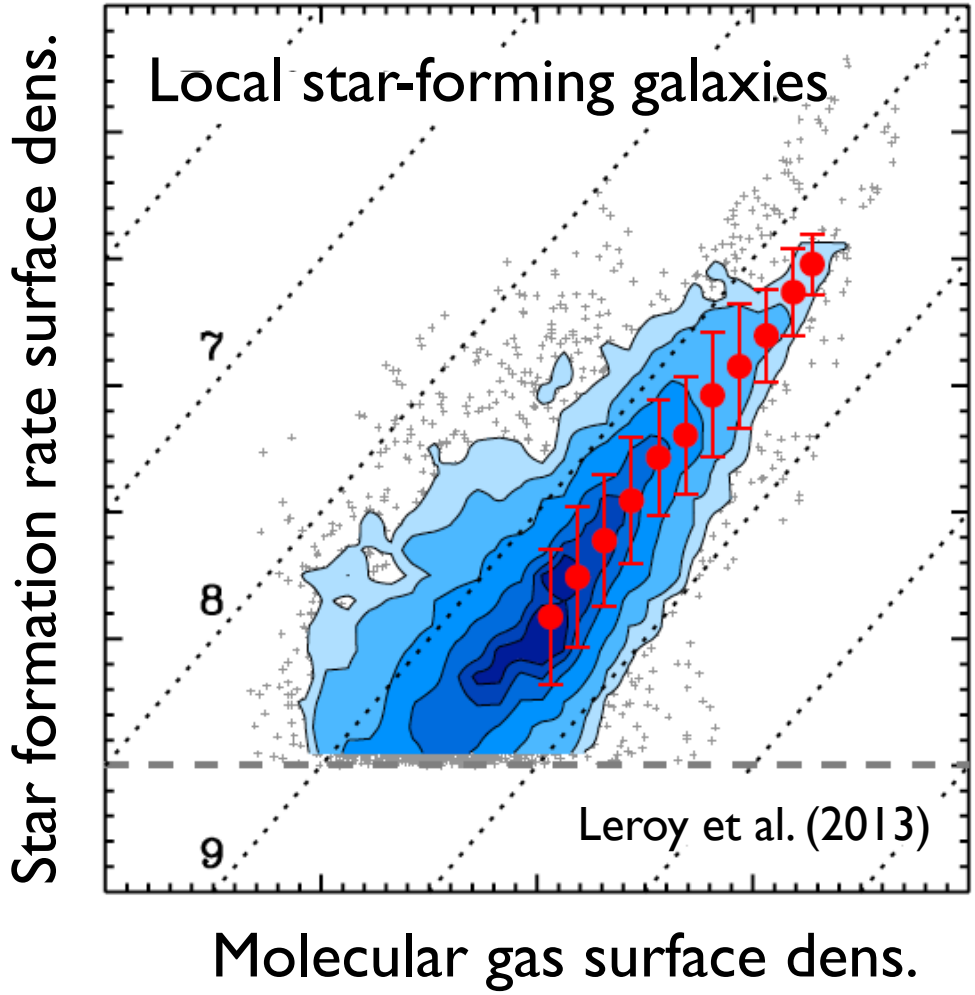
- Conversion into stars



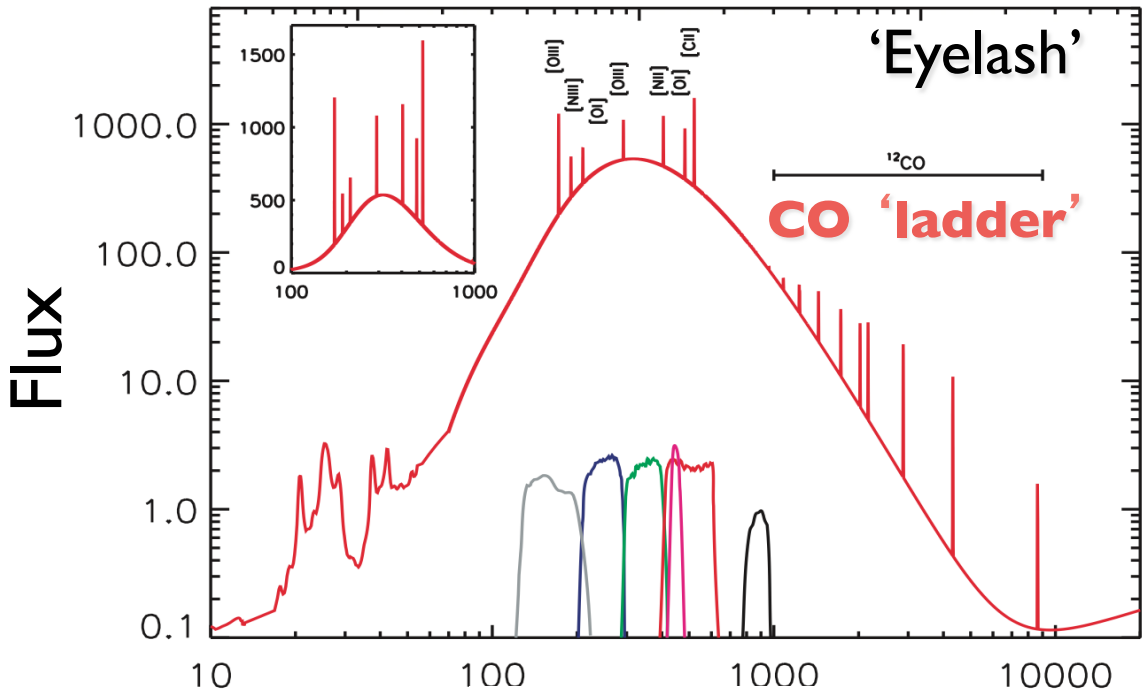
- Feedback



The star formation 'law'



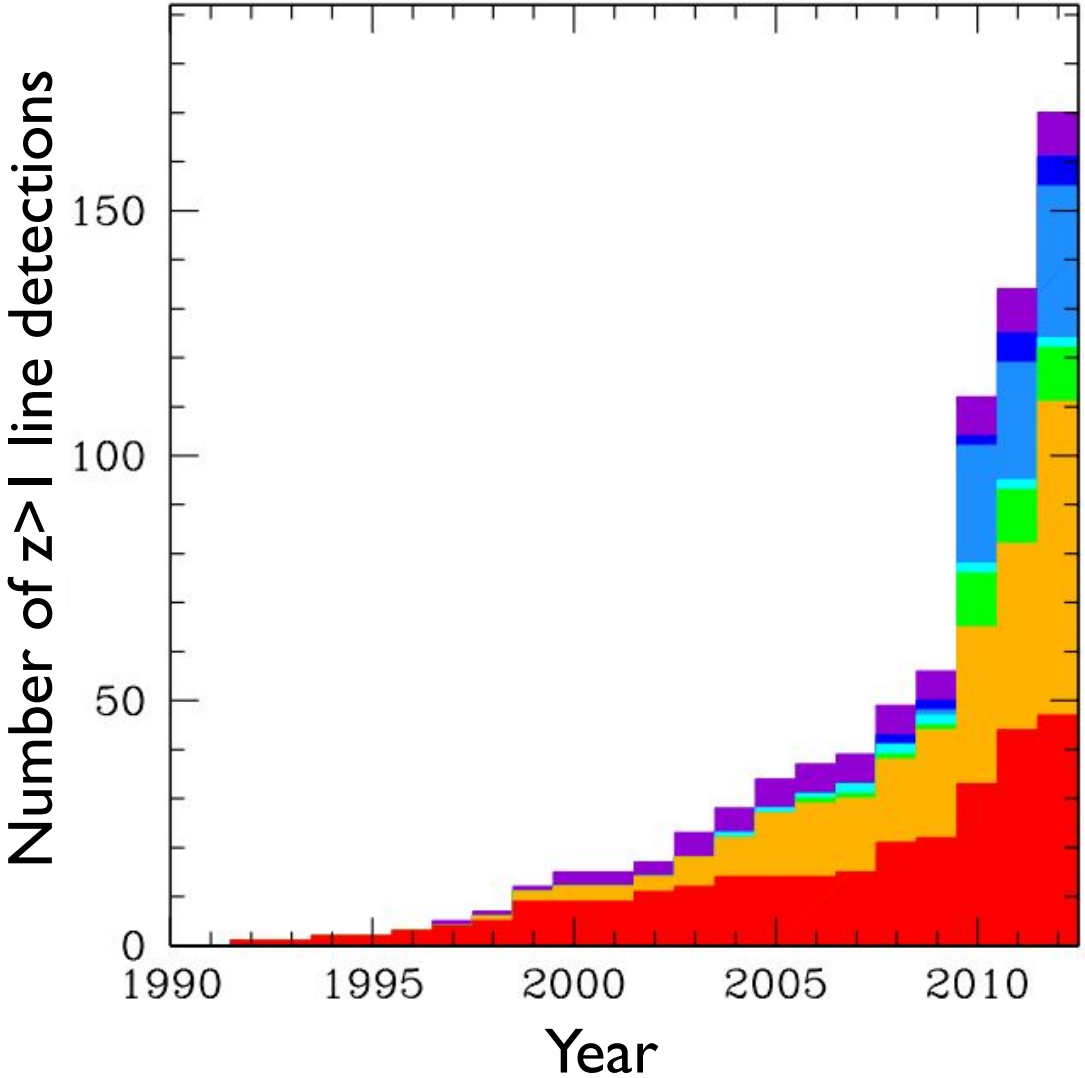
Tracing molecular gas with ^{12}CO



Smail et al. (2011)
Swinbank et al. (2011)

Requires CO-to-H_2 conversion factor 'α_{CO}'

High-z molecular gas detections



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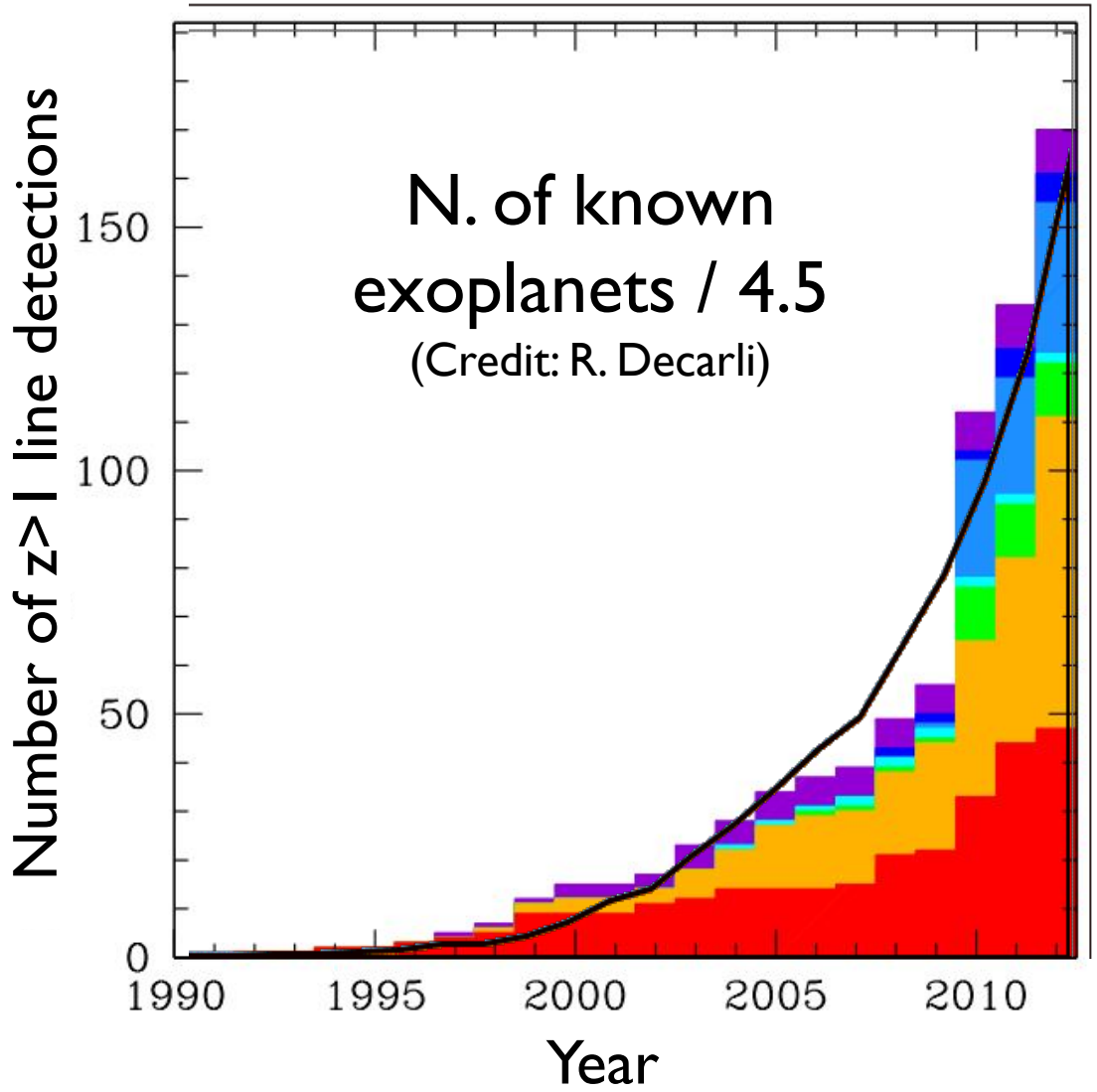
Carilli & Walter (2013)

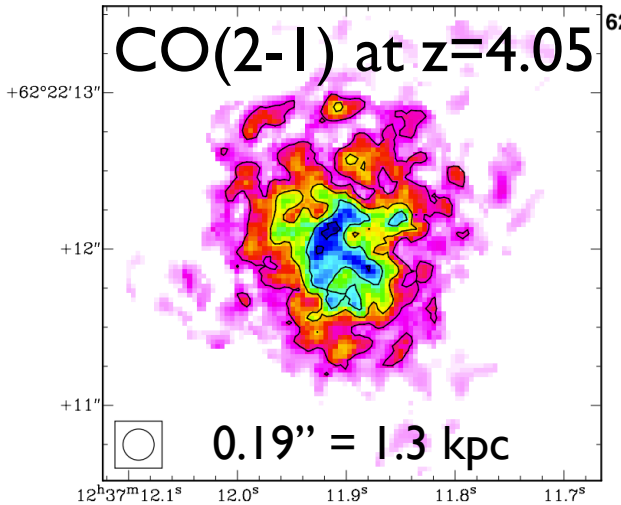
High-z molecular gas detections

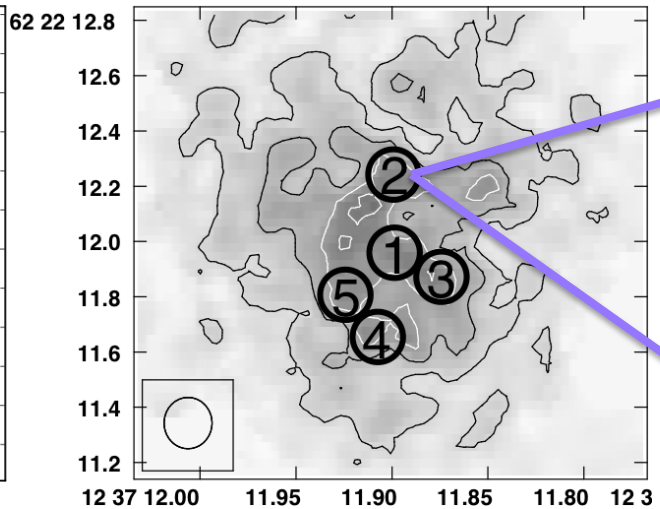


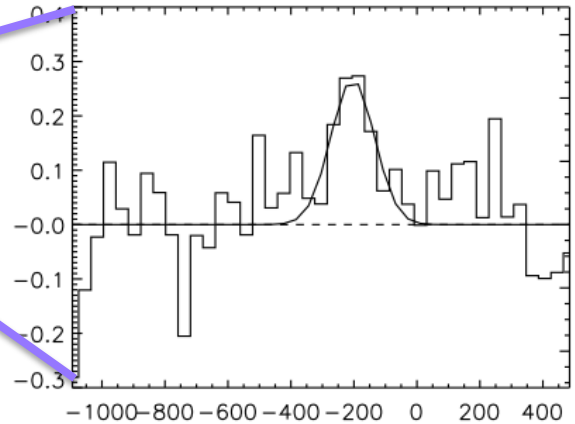
Carilli & Walter (2013)

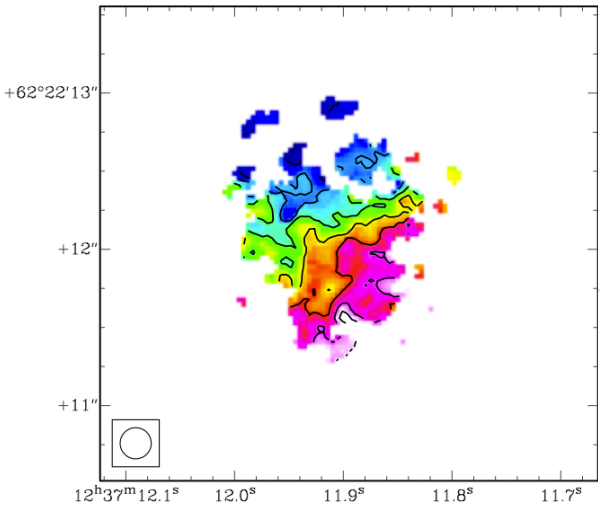
Beyond detection…resolving!

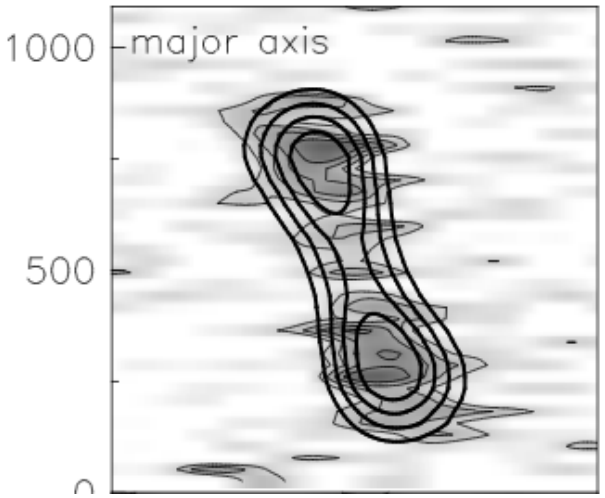
Hodge+12
see also Hodge+13c







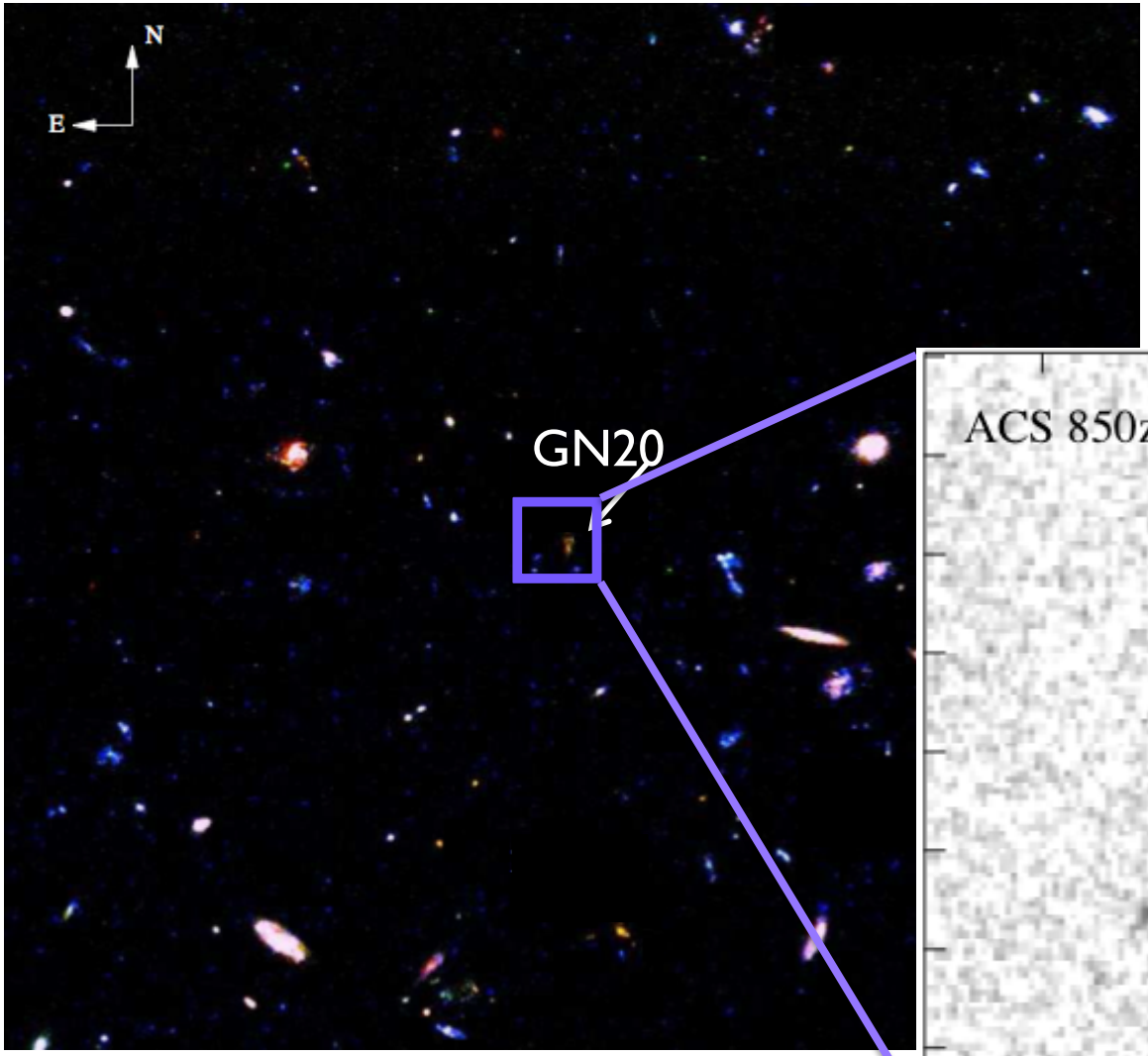




Clump properties:

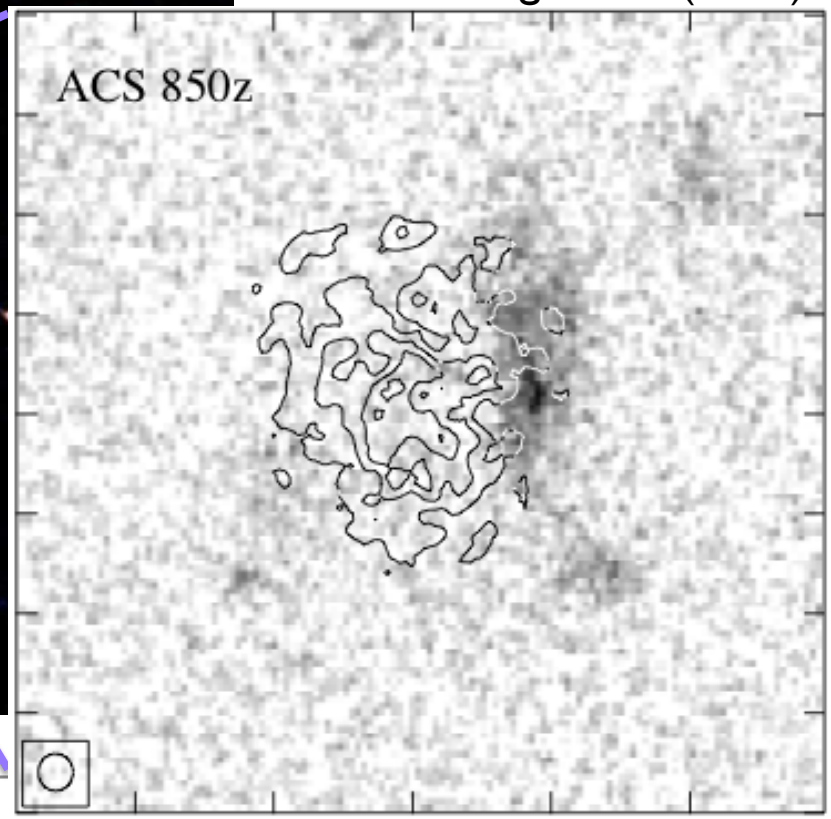
- T_B = 16-32 K ~ T_{dust}
- Size ~ 1 kpc
- Mass ~ 10^9 $M_\odot$
- Densities ~ 100 cm^{-3}

Gas vs. Stars



Daddi et al. (2009)

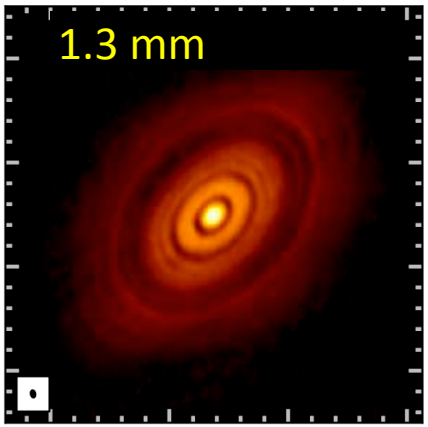
Hodge et al. (2012)



Atacama Large Millimeter Array (ALMA)

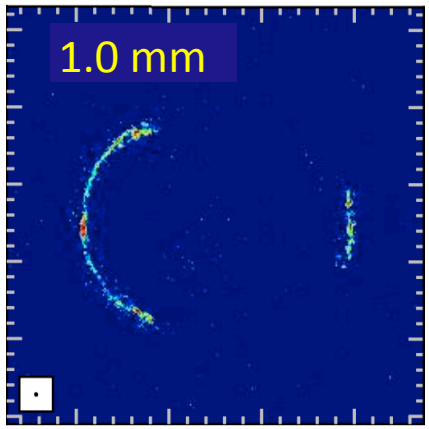
- Chajnantor plateau (5000m)
- 54 12-m antennas, 12 7-m
- 10 bands, 31-950 GHz
- 8 GHz bandwidth, dual polarization
- Array configs between 150m and 15-18 km
- Angular resolution ~40mas at 100 GHz (5mas at 900 GHz)

HL Tau



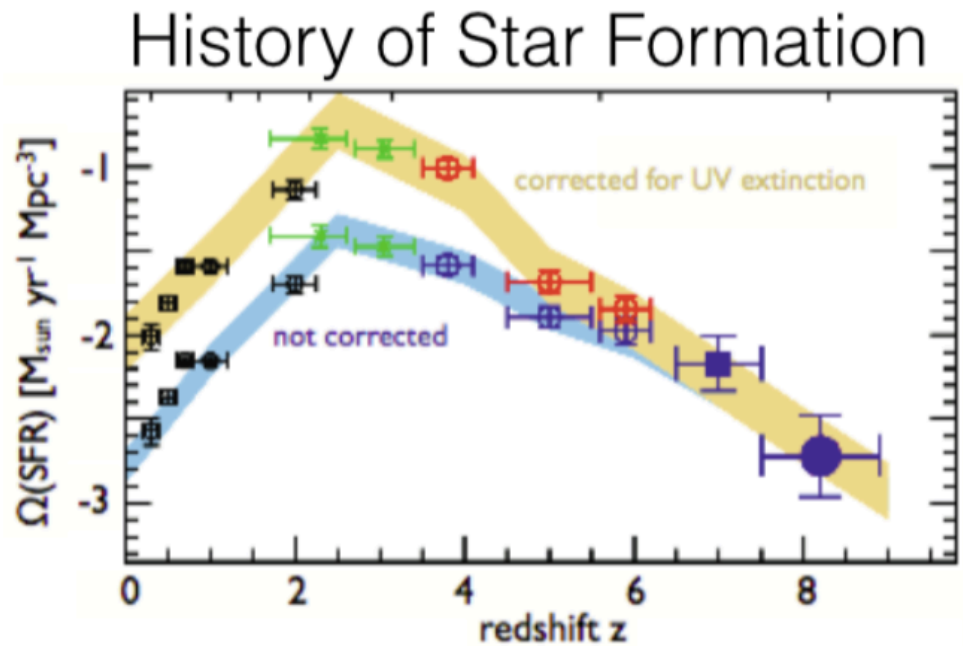
The ALMA Partnership, Brogan et al. (2015)

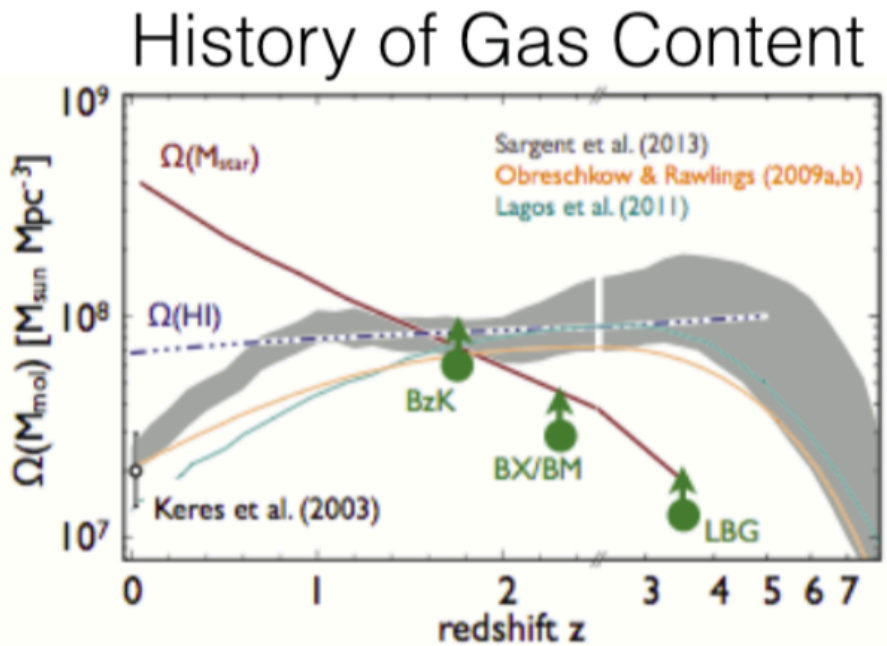
SDP.81



The ALMA Partnership, Vlahakis, Hunter, Hodge et al. (2015)

Ground+Space: *The history of cosmic SF*



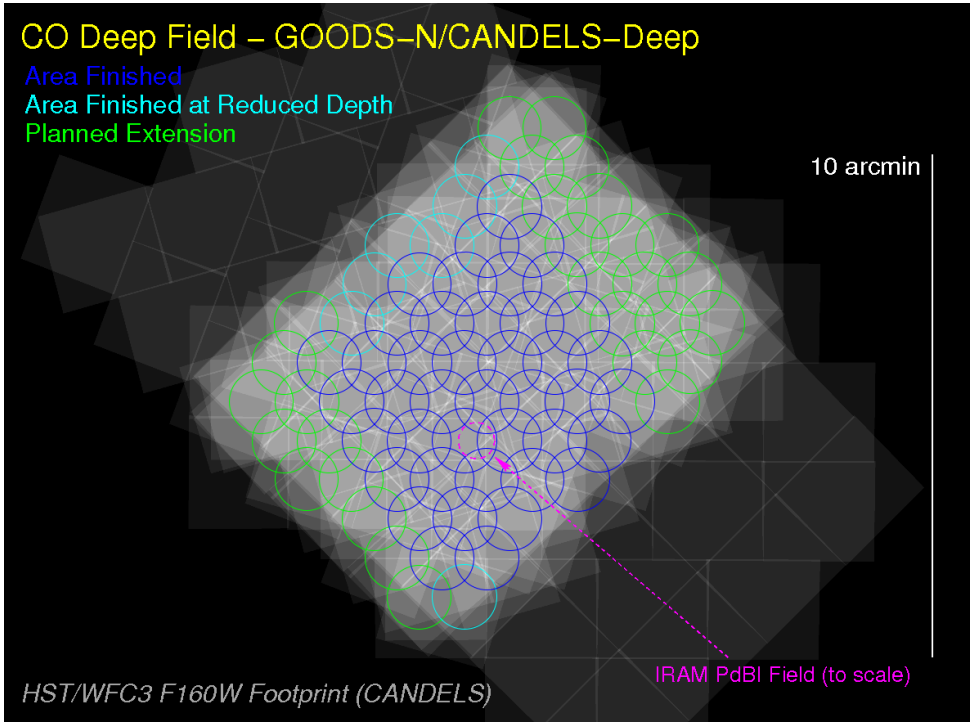


JWST

JVLA, ALMA

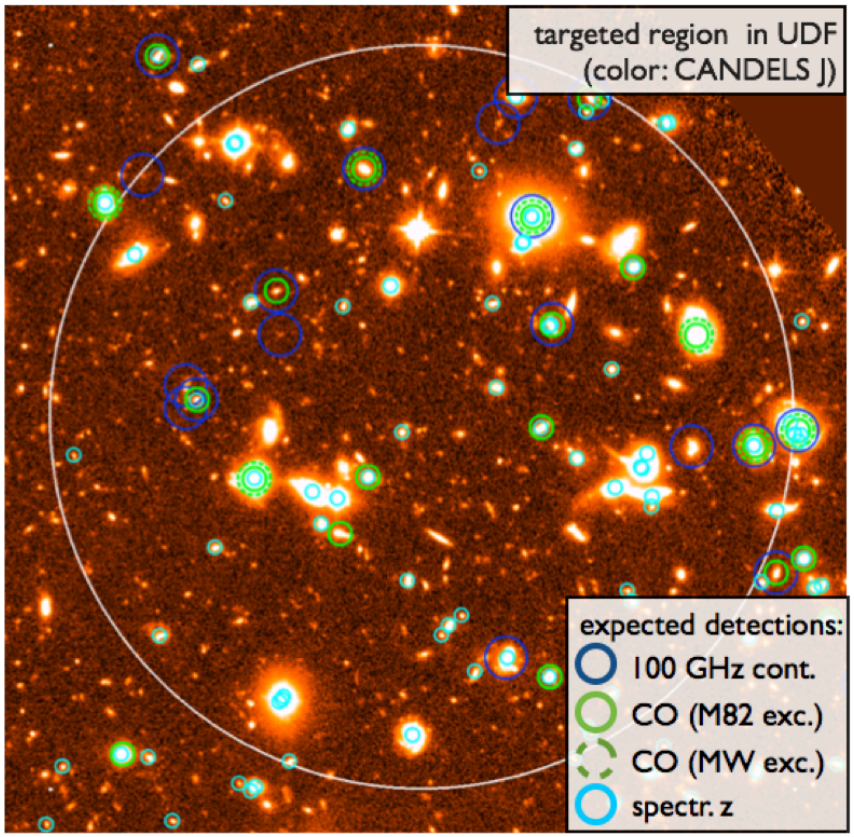
Ground+Space: *The history of cosmic SF*

JVLA CO Deep Fields



PI: Riechers

ALMA CO/C+ Deep Field



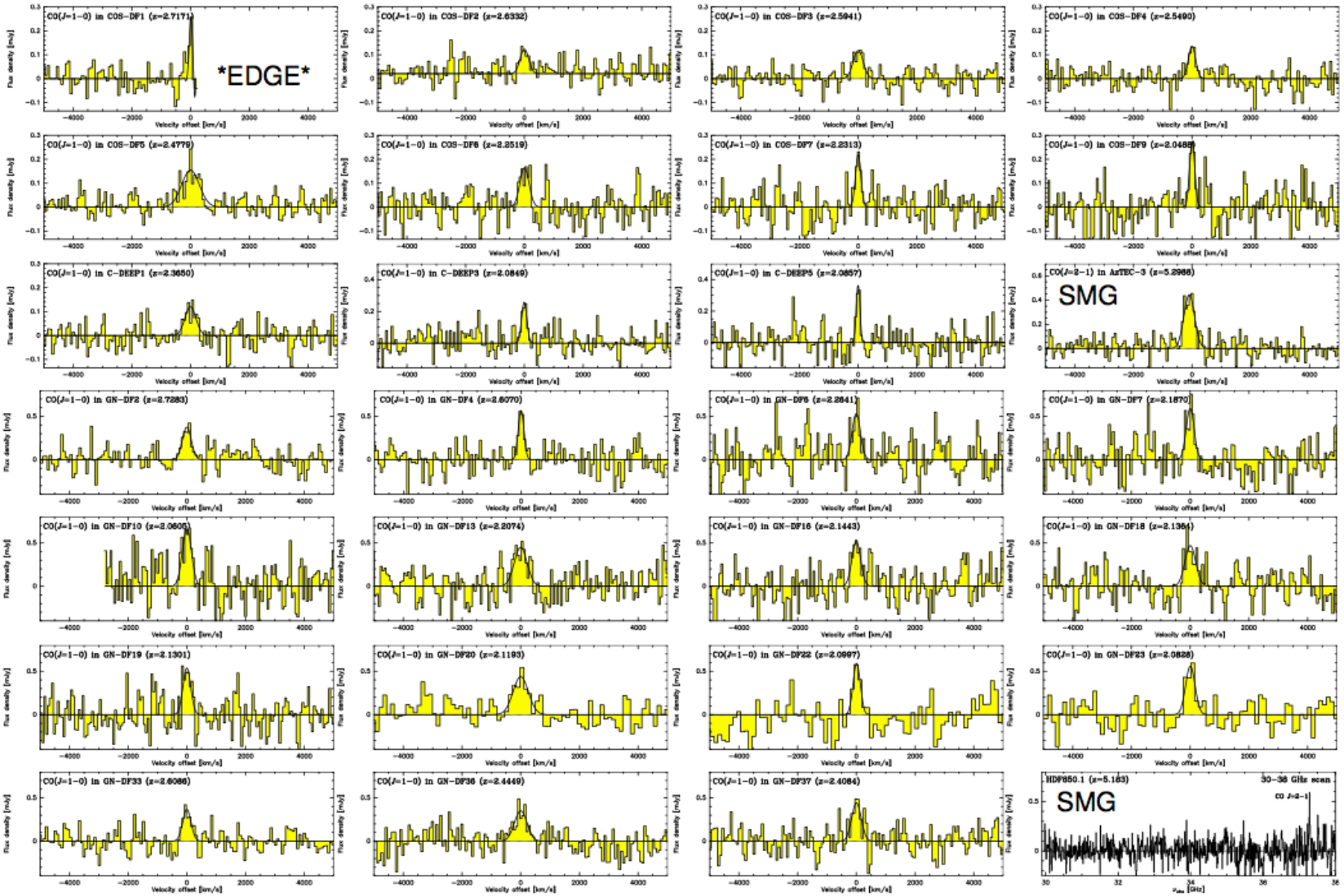
PI: Walter/Aravena

Ground+Space: *High-z galaxy confirmation*

[censored]

Ground+Space: *The history of cosmic SF*

Riechers/Pavesi in prep.



Ground+Space: *The history of cosmic SF*

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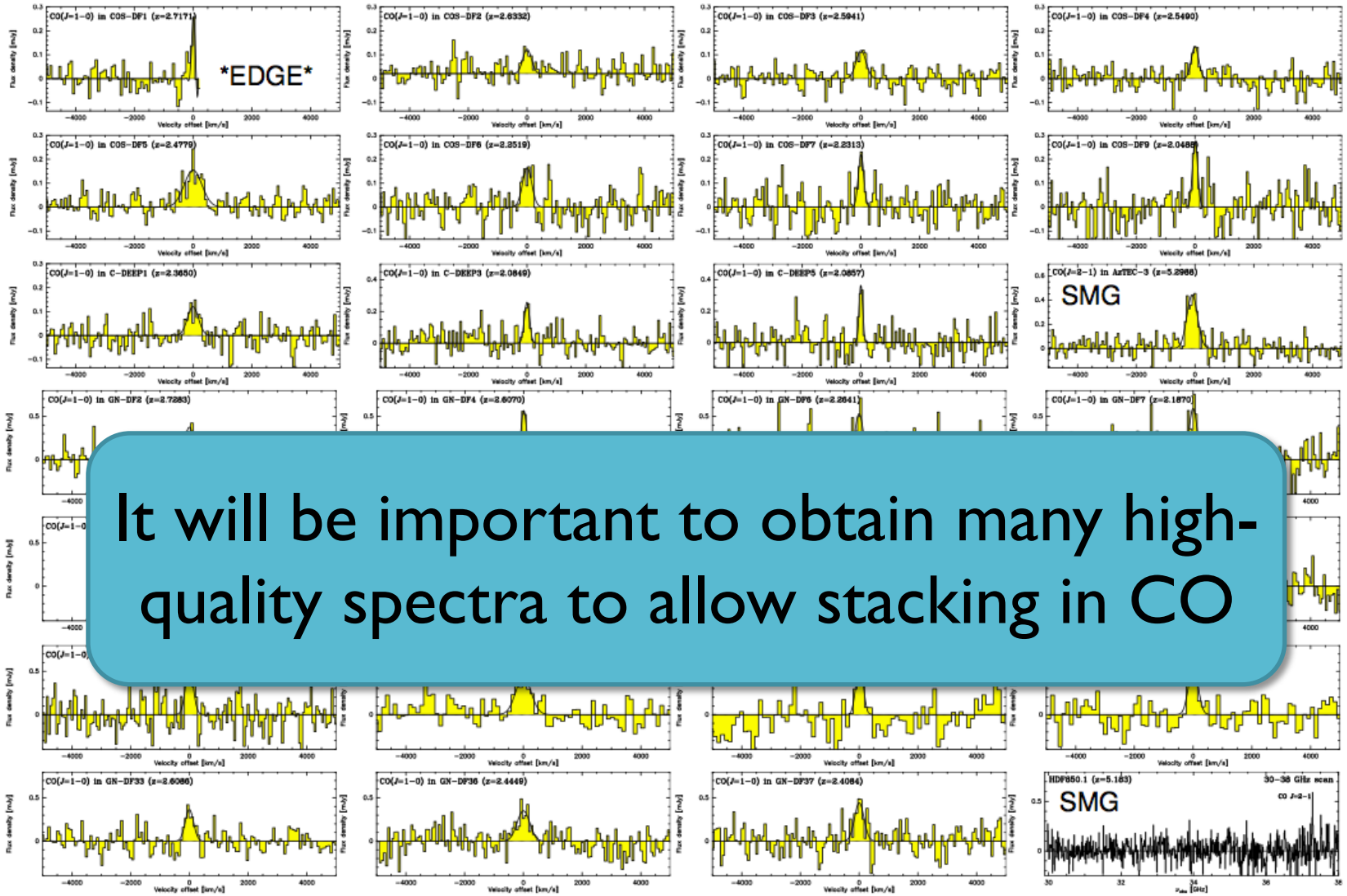
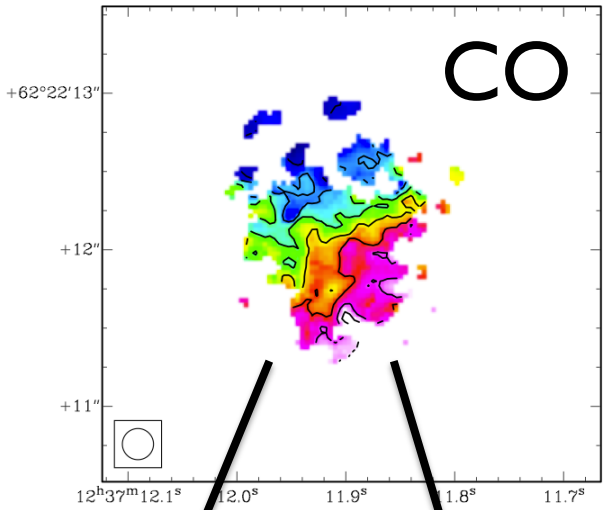


It will be important to obtain many high-quality spectra to allow stacking in CO

Ground+Space: *Dynamics & Mass census*



Merger

Disk

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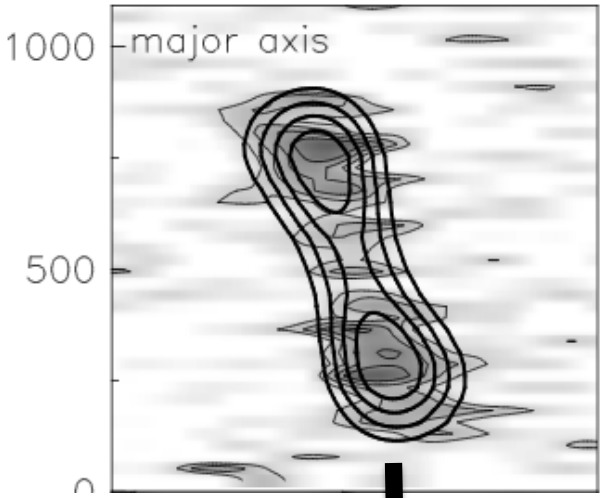
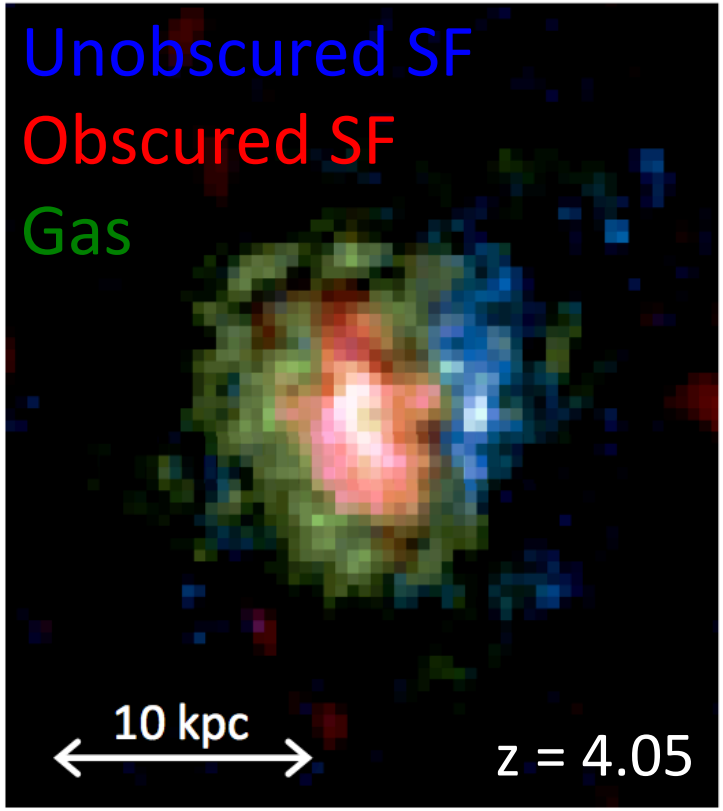
Hodge et al. (2012)



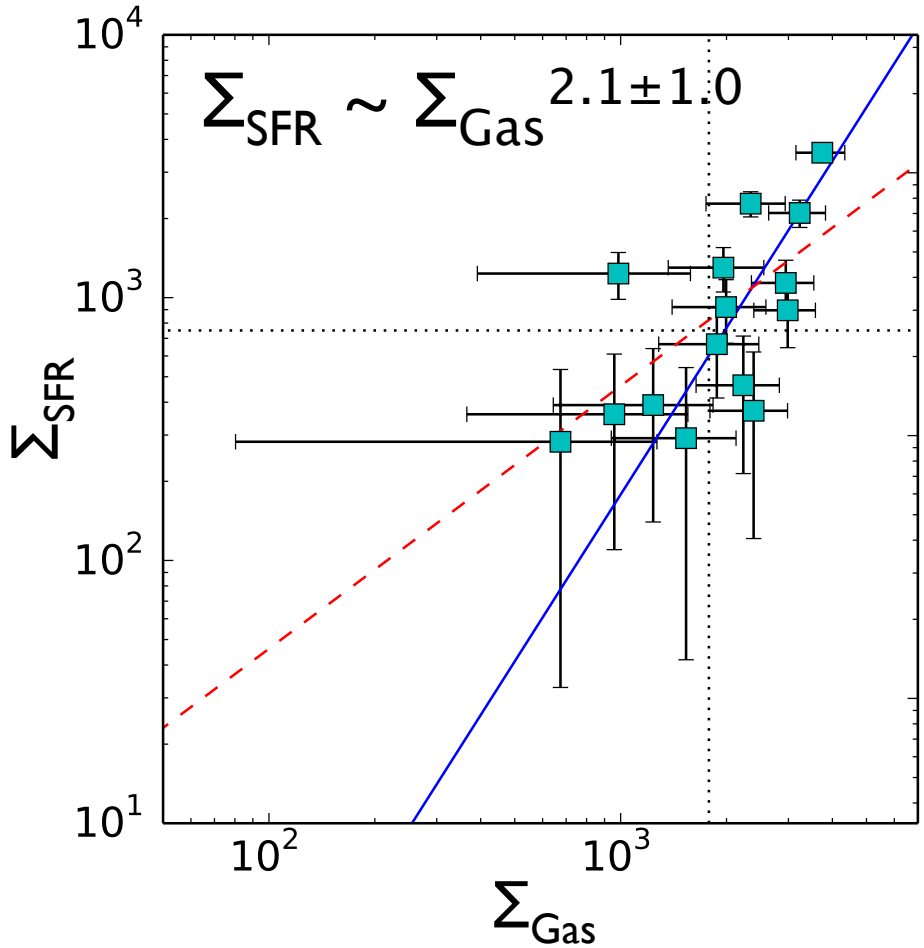
M_{dyn} ,
$M_{stellar}$ (JWST)

M_{gas} , α_{CO}

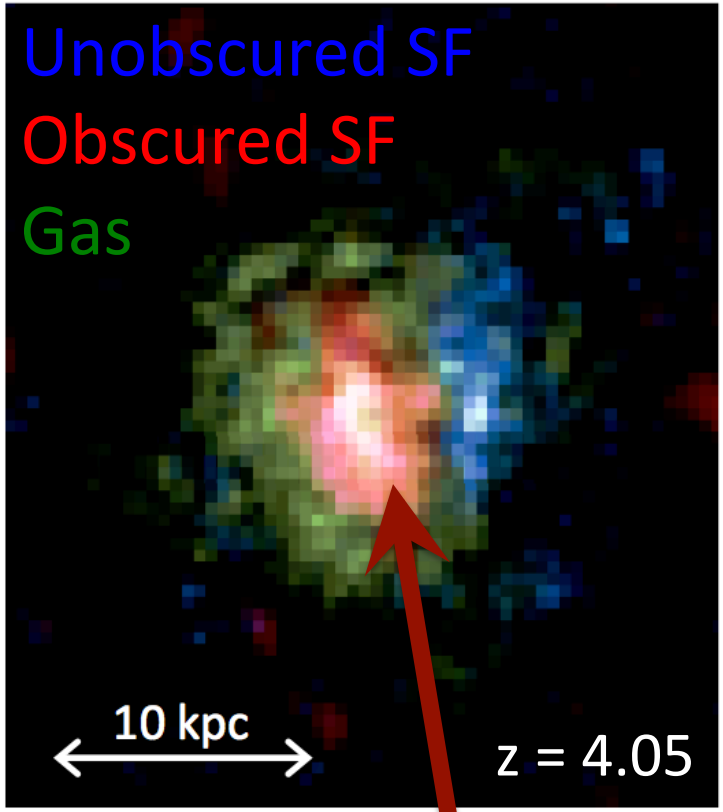
Ground+Space: *(sub-)kpc-scale SF*



Hodge et al. (2015)



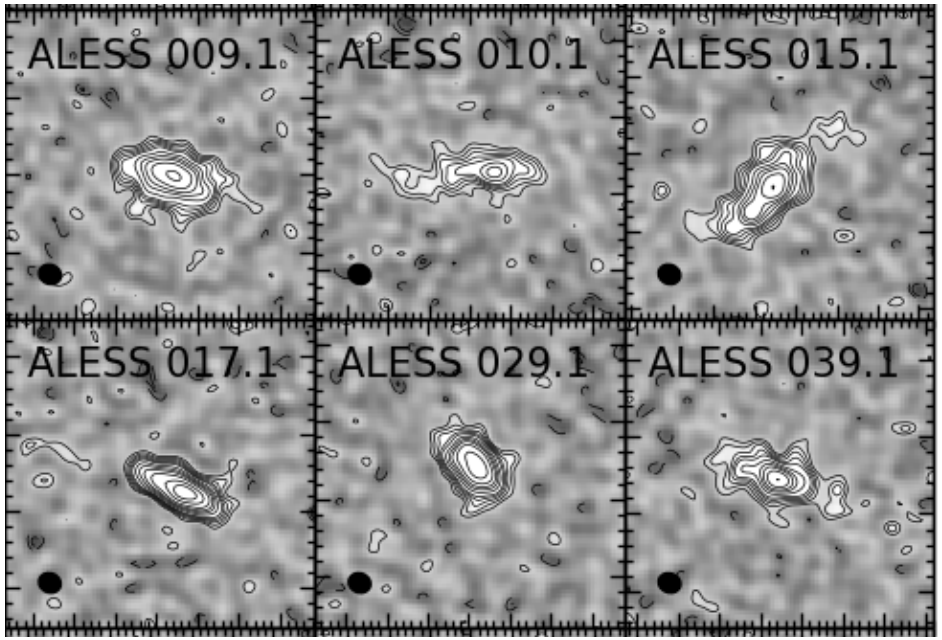
Ground+Space: *(sub-)kpc-scale SF*



Hodge et al. (2015)

12 hours on PdBI to achieve
2 kpc resolution dust imaging

New ALMA Cycle 1 data achieve
1 kpc in just ***10 min*** per source



Hodge et al. (2016, in prep)

Ground+Space: *(sub-)kpc-scale SF*

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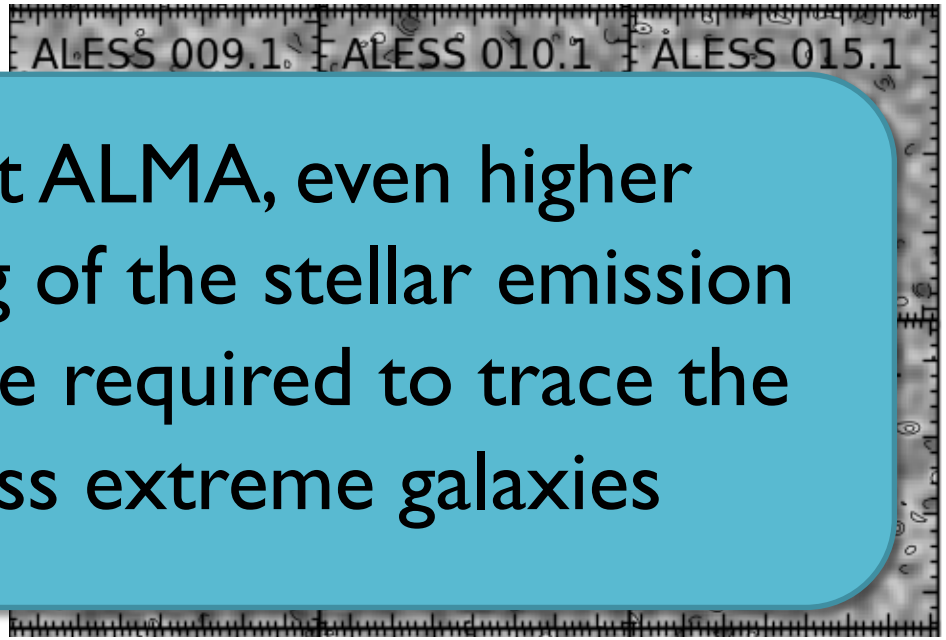


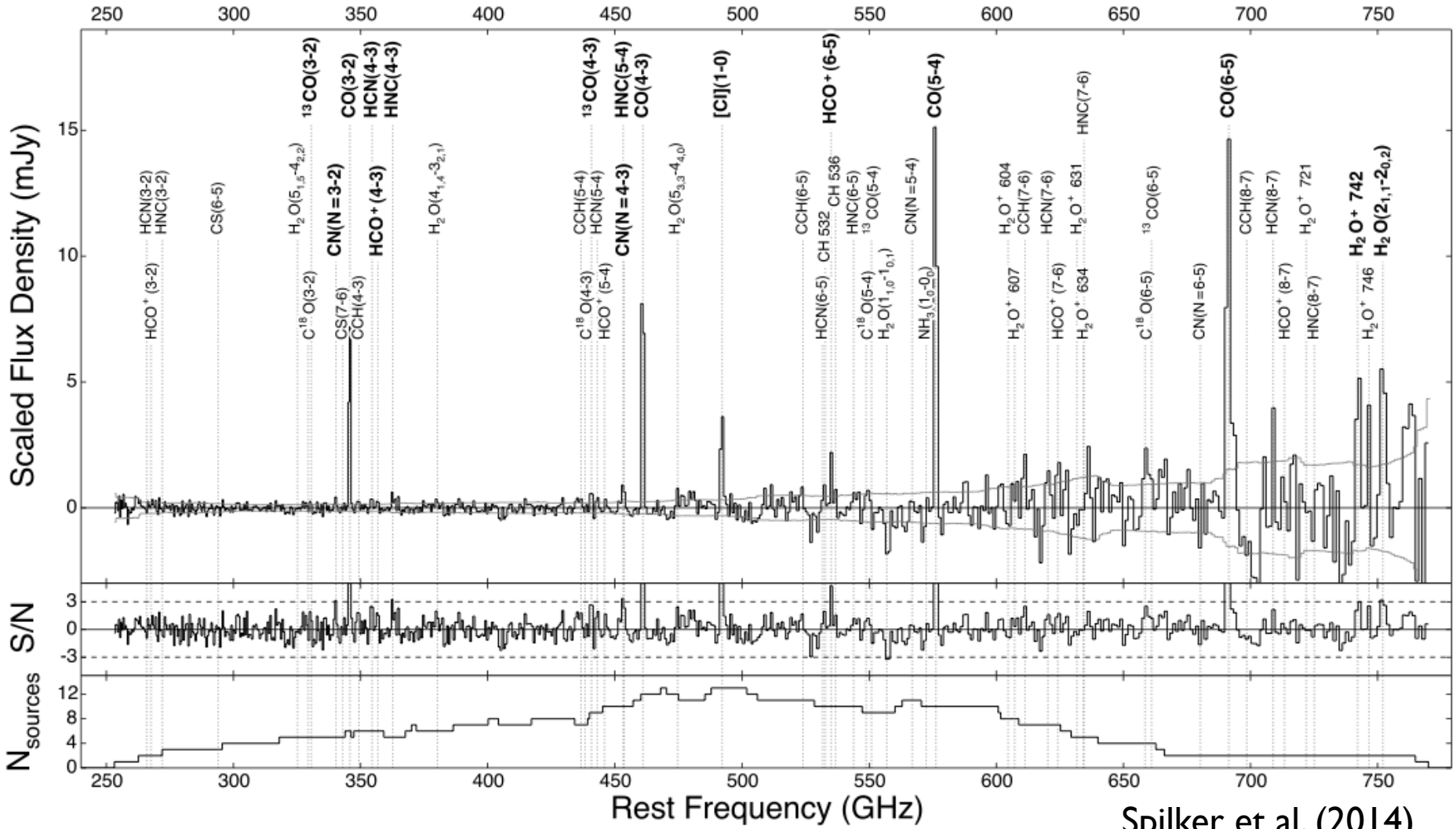
Hodge et al. (2016, in prep)

To complement ALMA, even higher resolution imaging of the stellar emission (e.g. HDST) will be required to trace the **total** SF in less extreme galaxies

12 hours on PdBI to achieve
2 kpc resolution dust imaging

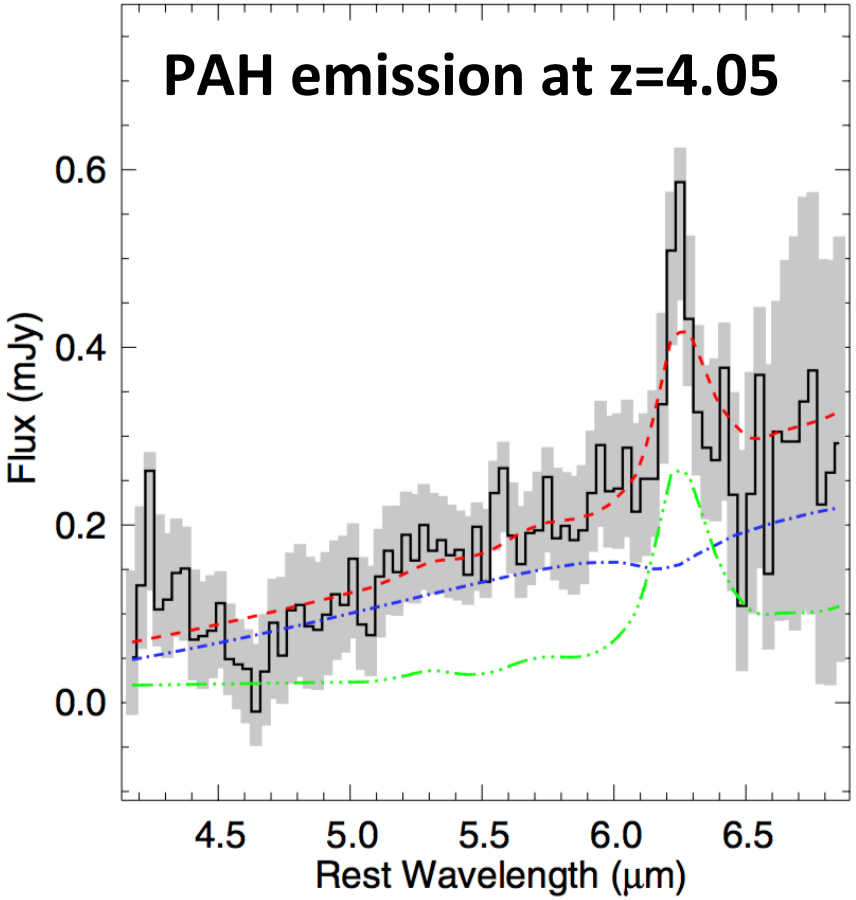
Ground+Space: *ISM Characterization*

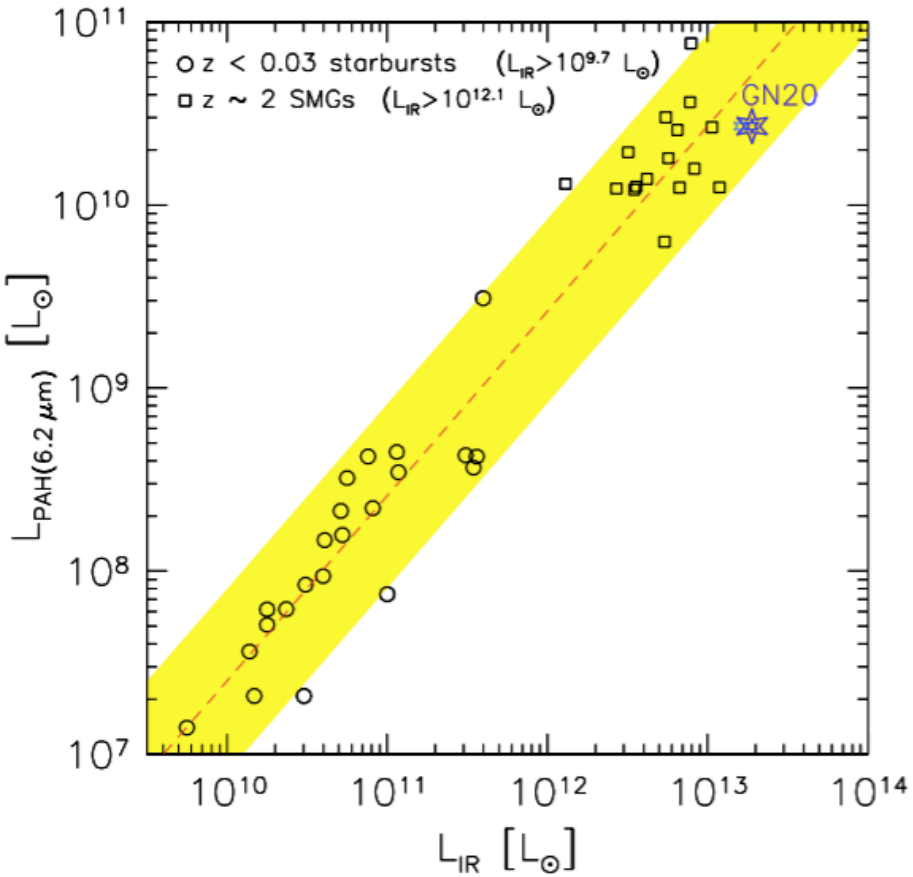
Composite spectrum from 22 lensed SMGs from ALMA Cycle 0



Spilker et al. (2014)

Ground+Space: *ISM Characterization*

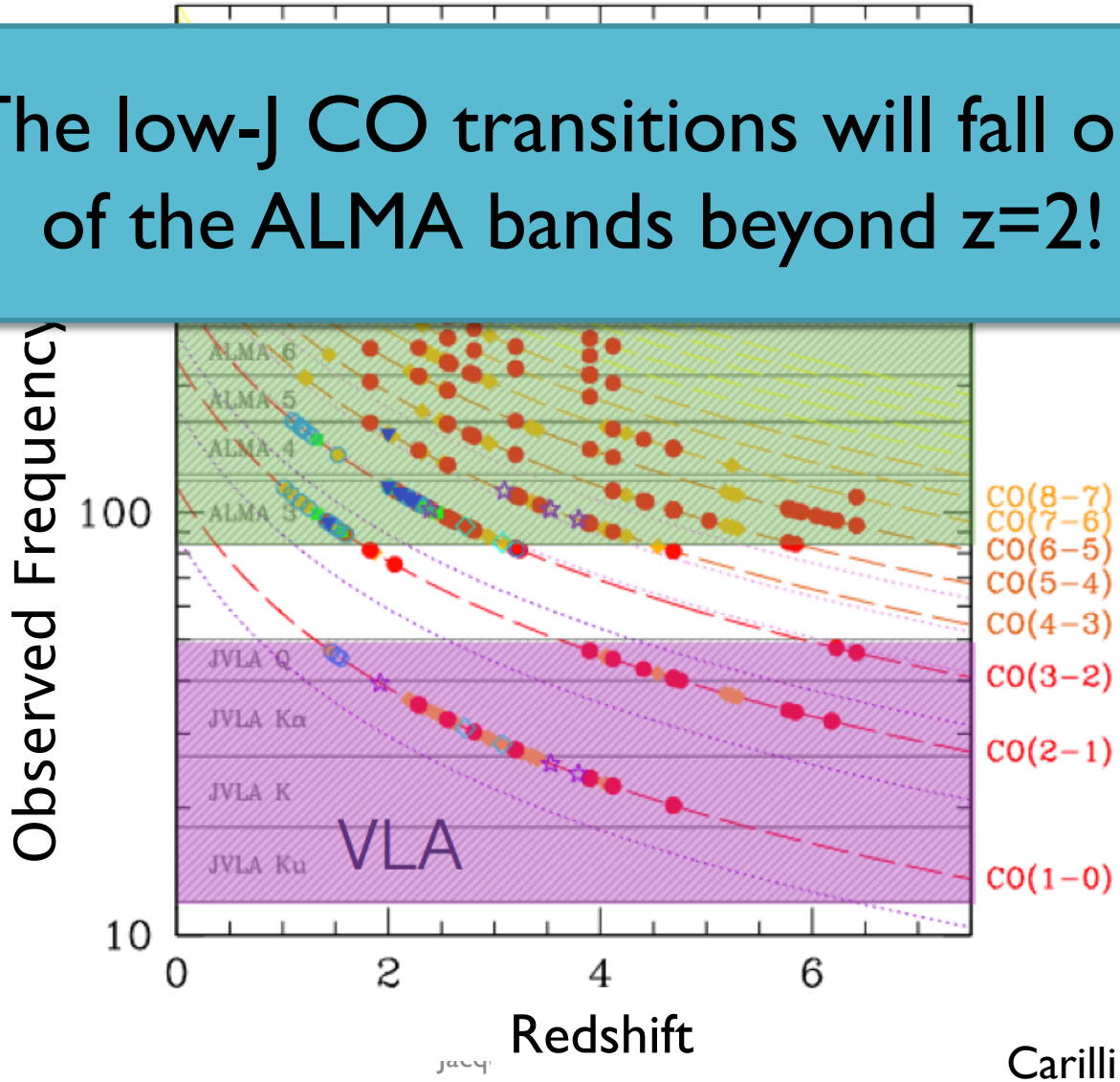




Riechers et al. (2014)

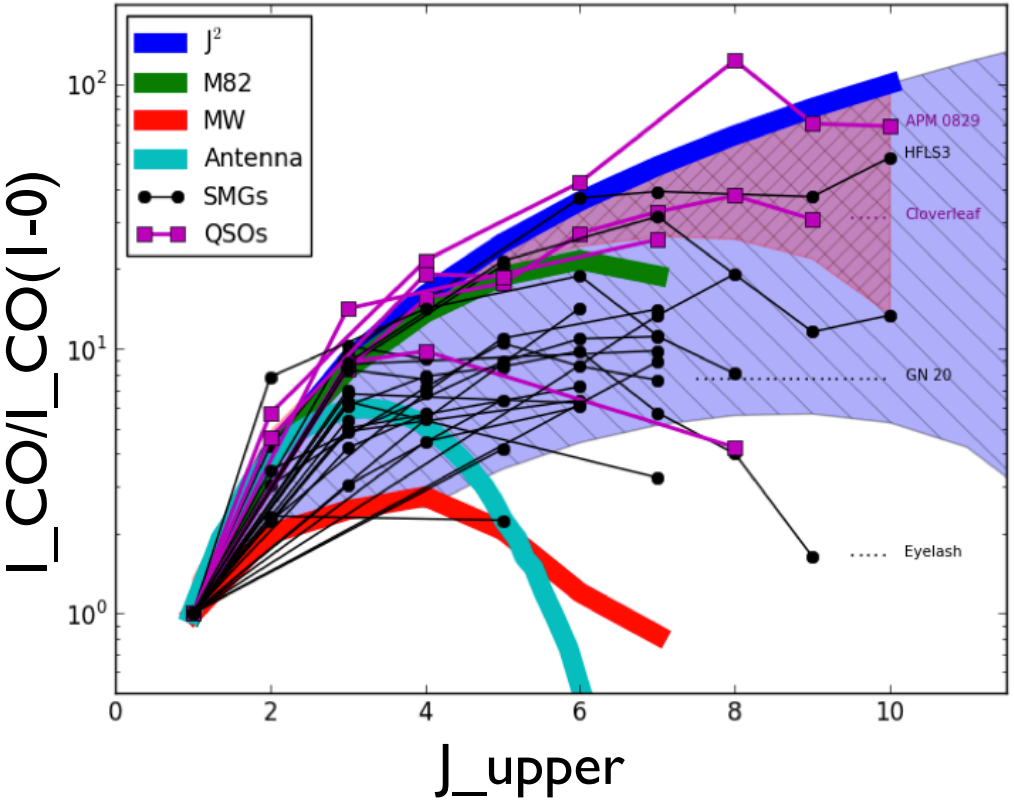
The need for a next-generation VLA

The low-J CO transitions will fall out of the ALMA bands beyond z=2!



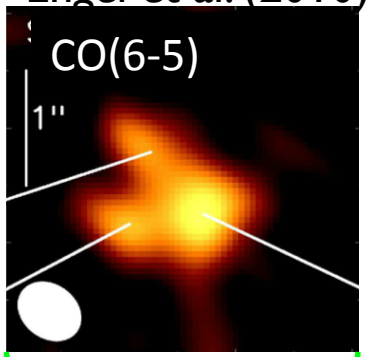
Carilli & Walter 2013

Low-J CO is critical

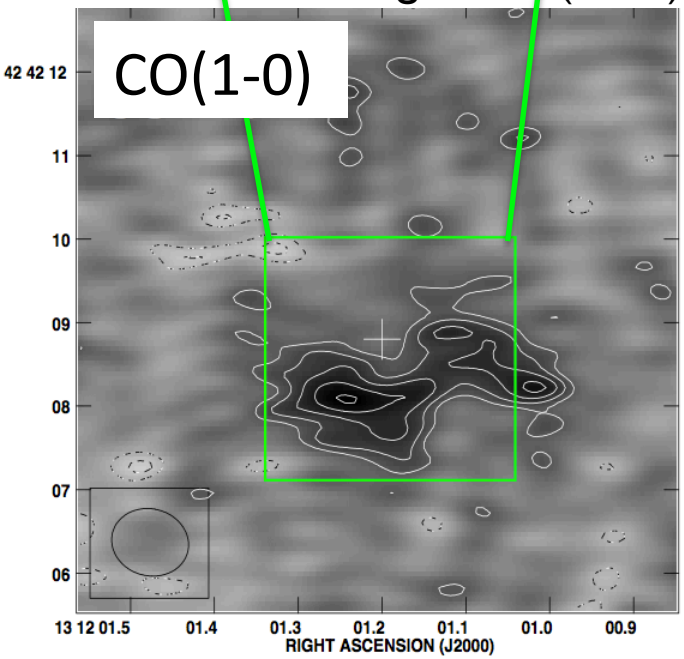


Casey, Narayanan & Cooray 2014

Engel et al. (2010)

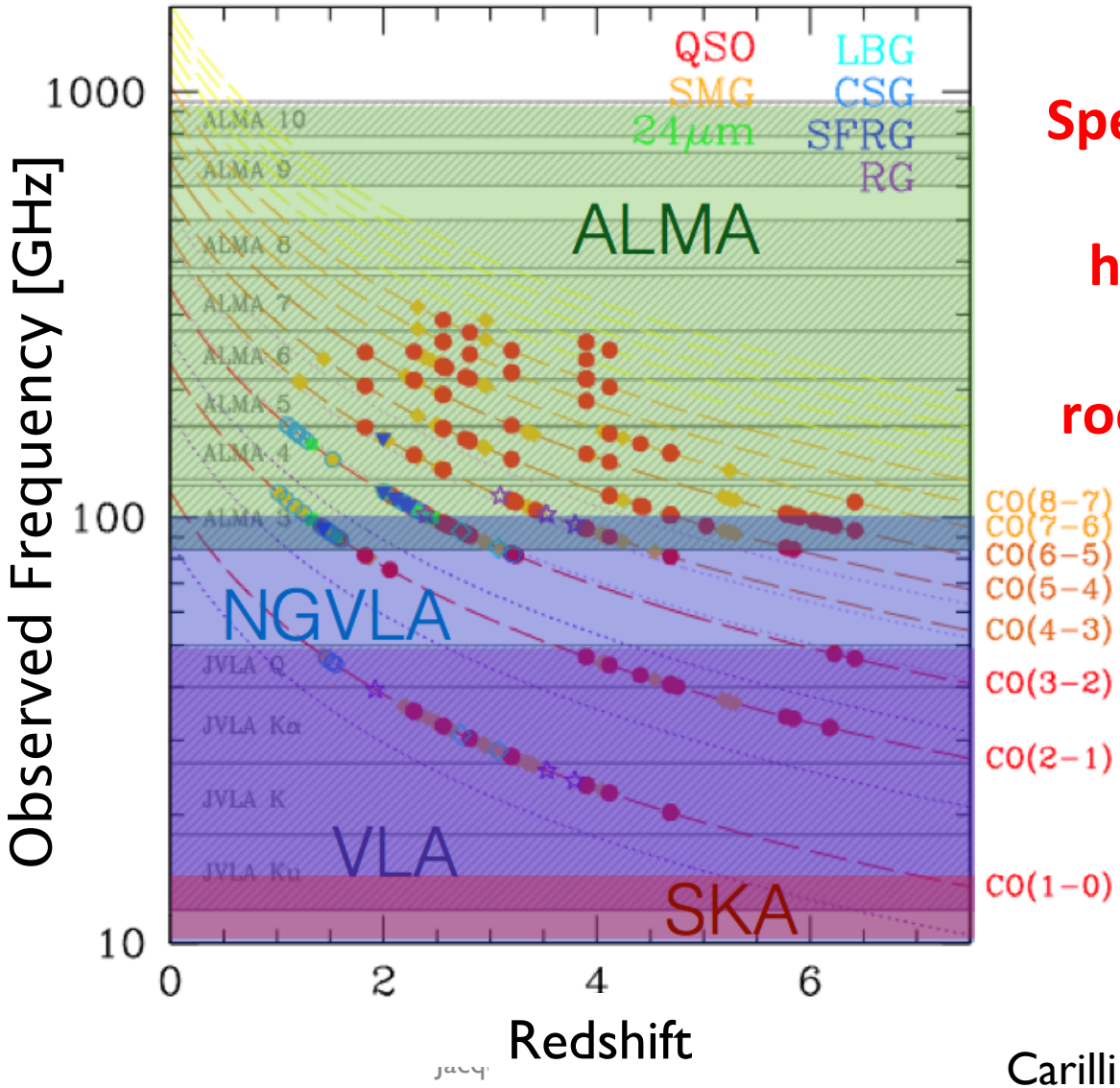


Riechers, Hodge et al. (2011)



THE VERY LARGE ARRAY

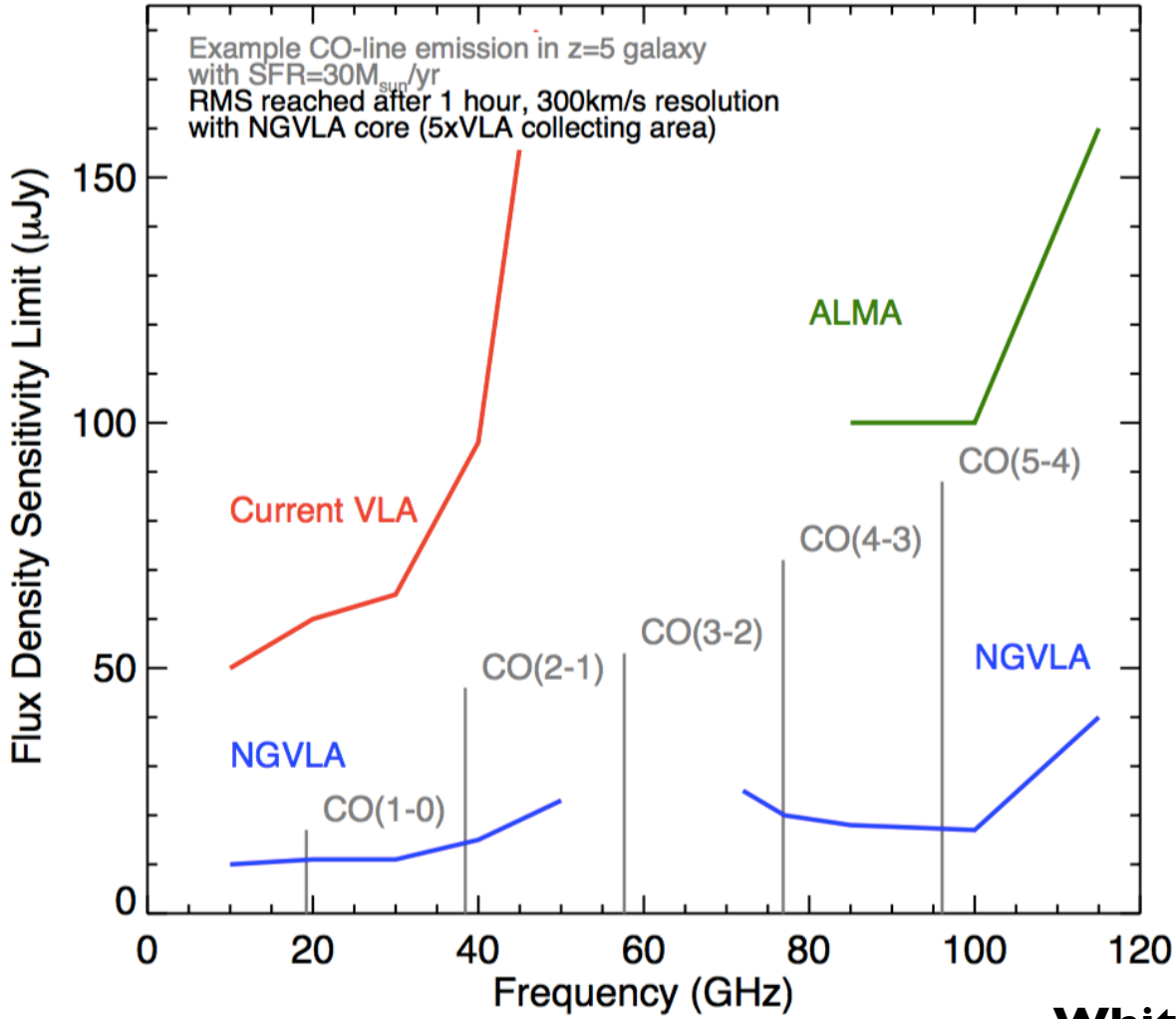
THE NEXT GENERATION



Special ngVLA session happening today in room 'Sun B'

Carilli & Walter 2013

THE VERY LARGE ARRAY
THE NEXT GENERATION



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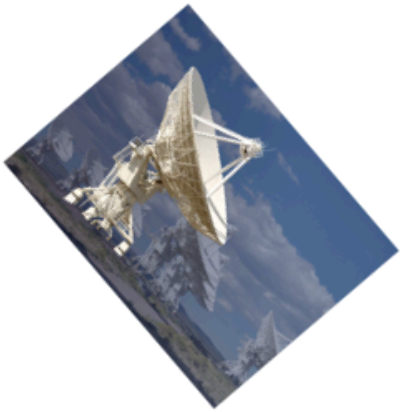
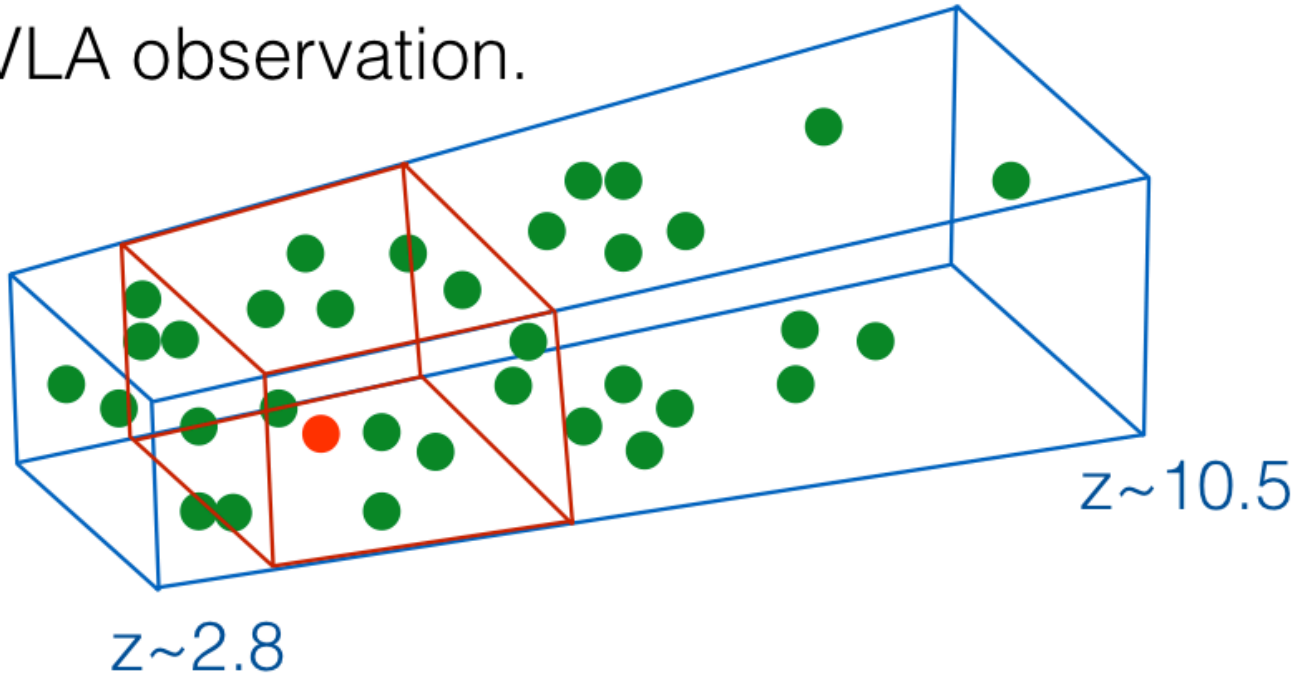
White Paper:
Casey, Hodge, Lacy et al (2015)

An example ngVLA observation.





Critical to complement e.g., JWST, SPICA

Detectable with current VLA

e.g. z=4.05 CO(1-0)
L'co~10^{10} Lsun
8GHz bandwidth
3.2<z<5.0

Detectable with ngVLA

2.8<z<10.5 CO(1-0)
L'co~2x10^{9} Lsun
3:1 bandwidth ratio
100s of blind CO(1-0) detections!

Summary

- **Take-away points:**
  - ALMA is revolutionizing high-z molecular gas studies
  - Will need a ngVLA to trace bulk of cold gas at high-z
- **Space-based wish-list:**
  - Higher-resolution imaging of rest-frame UV emission
    - ALMA's most extended configs will reach scales of ~100 pc
  - Longer wavelength spectroscopy
    - Need MIR for ISM characterization
  - Lots of high-quality spectra
    - Until ngVLA, detecting CO still hard for many galaxies – will need to stack