Galaxies at high redshift: Insights from molecular line emission

Jacqueline Hodge

Jansky Fellow (NRAO)

Santiago, Chile

23 March 2015

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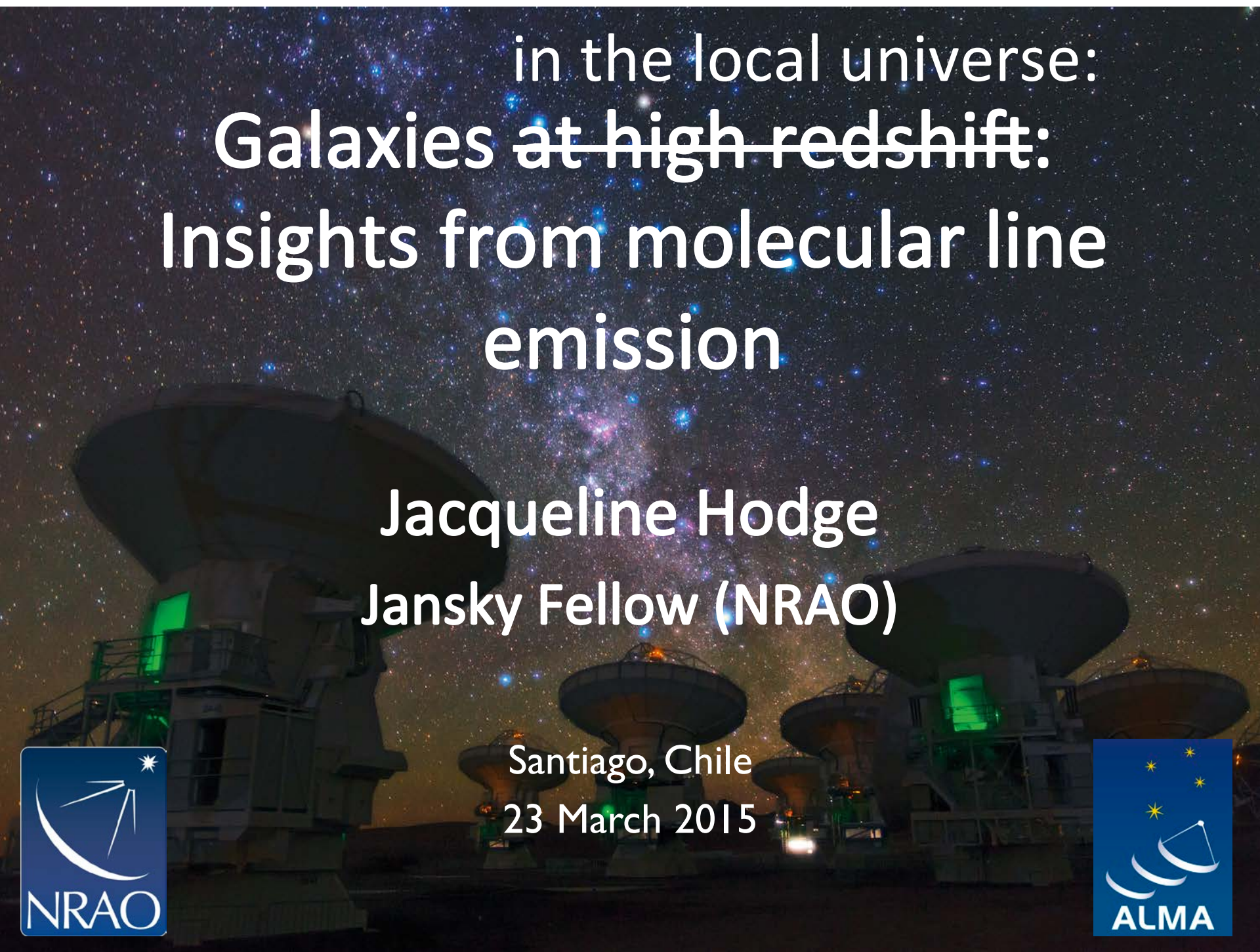

in the local universe: Galaxies ~~at high redshift~~: Insights from molecular line emission

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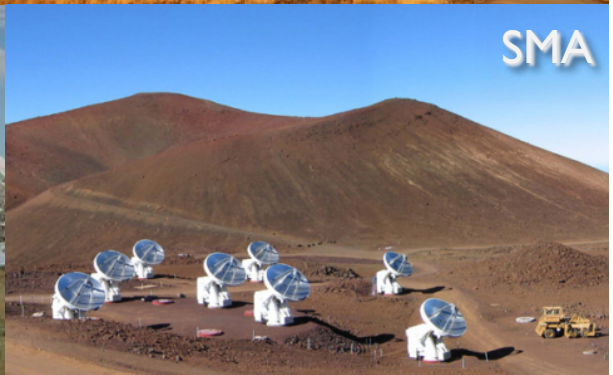
NRAO

ALMA

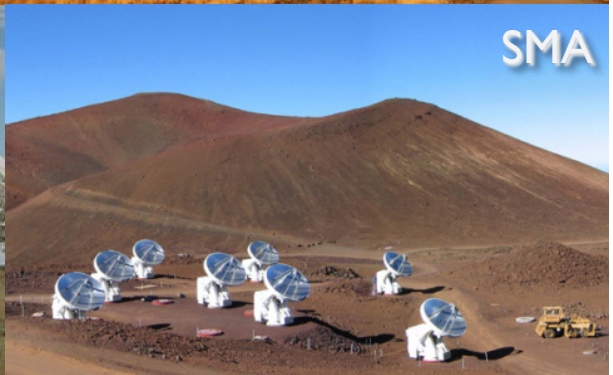
Outline

- Motivation
- Progress
  - Targeting FIR-bright sources
  - Targeting color-selected galaxies
  - Blind molecular deep fields
- The Future



Outline

- Things I won't cover:
  - Dense gas tracers
  - Fine structure lines (e.g., C+)
  - Molecular outflows
  - The effects of environment
  - Using dust to trace the molecular ISM



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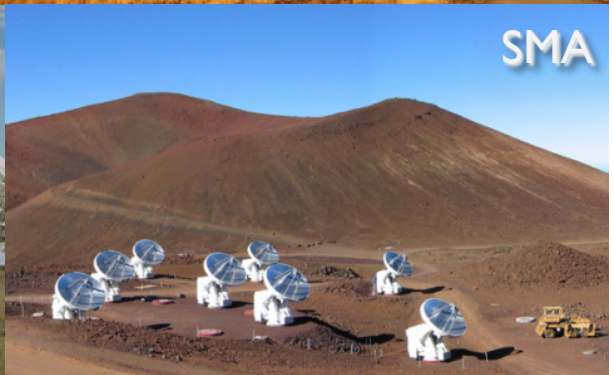

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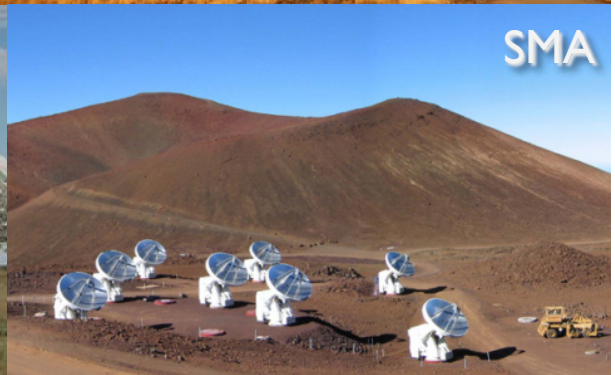
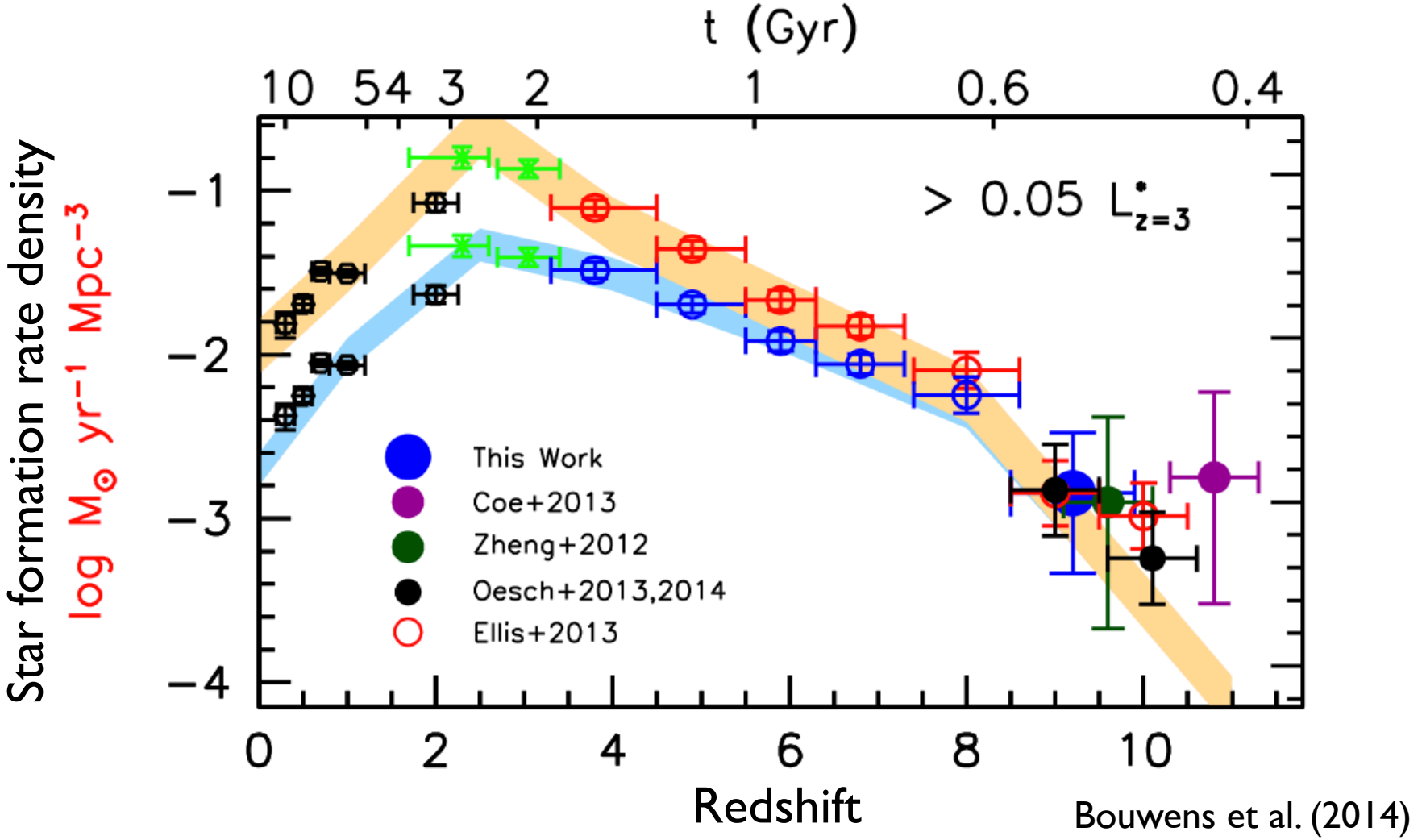


Star Formation History of the Universe



Bouwens et al. (2014)

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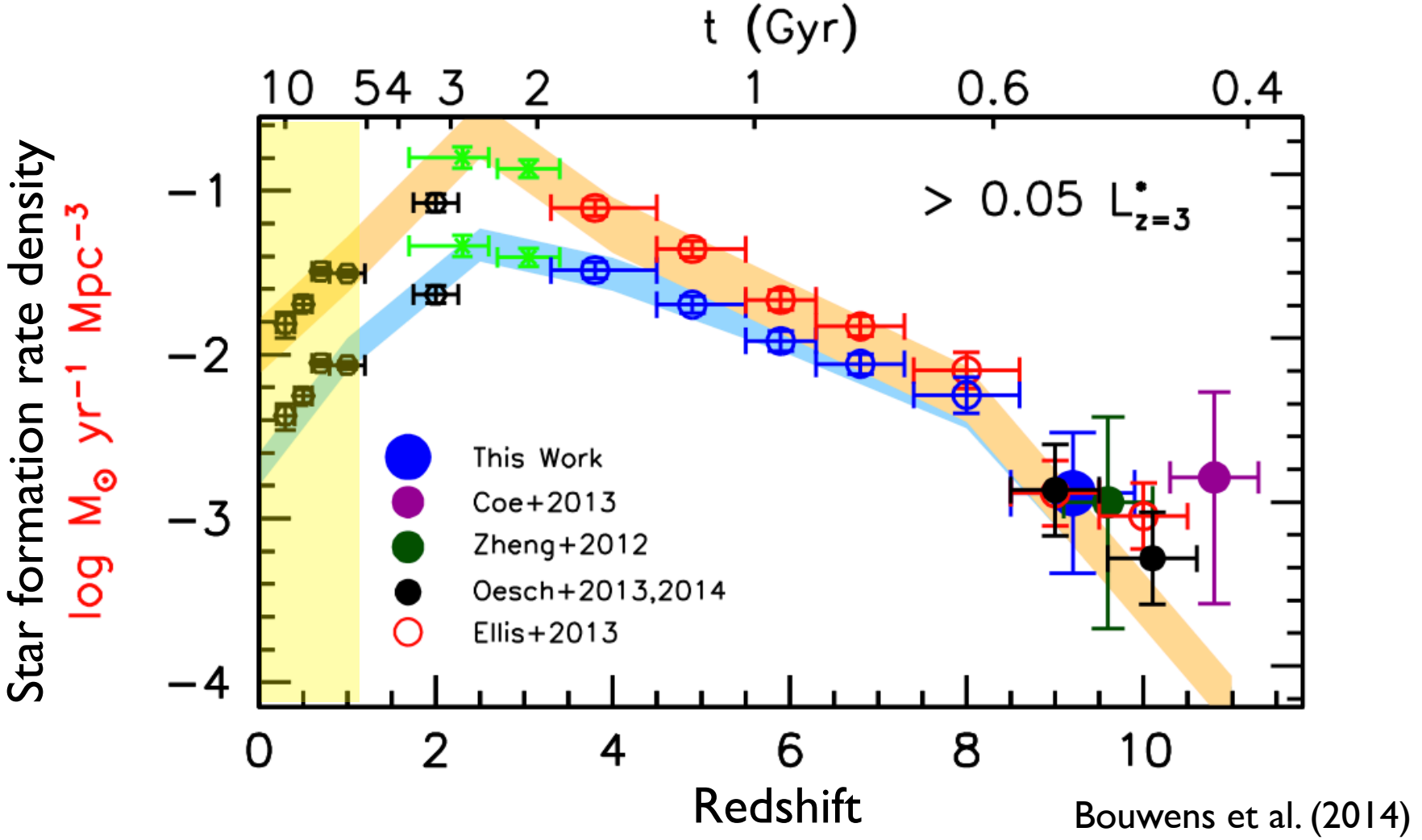

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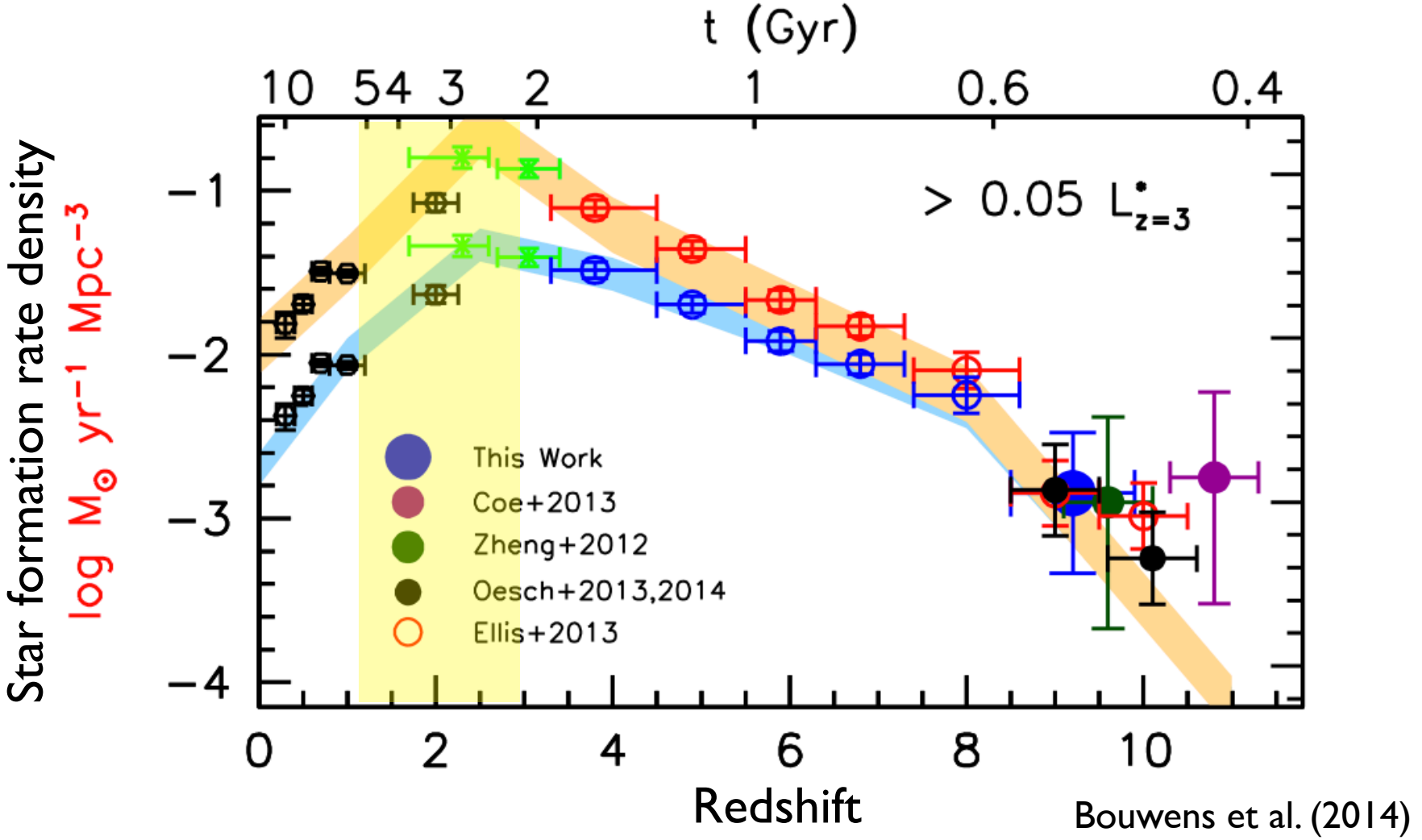

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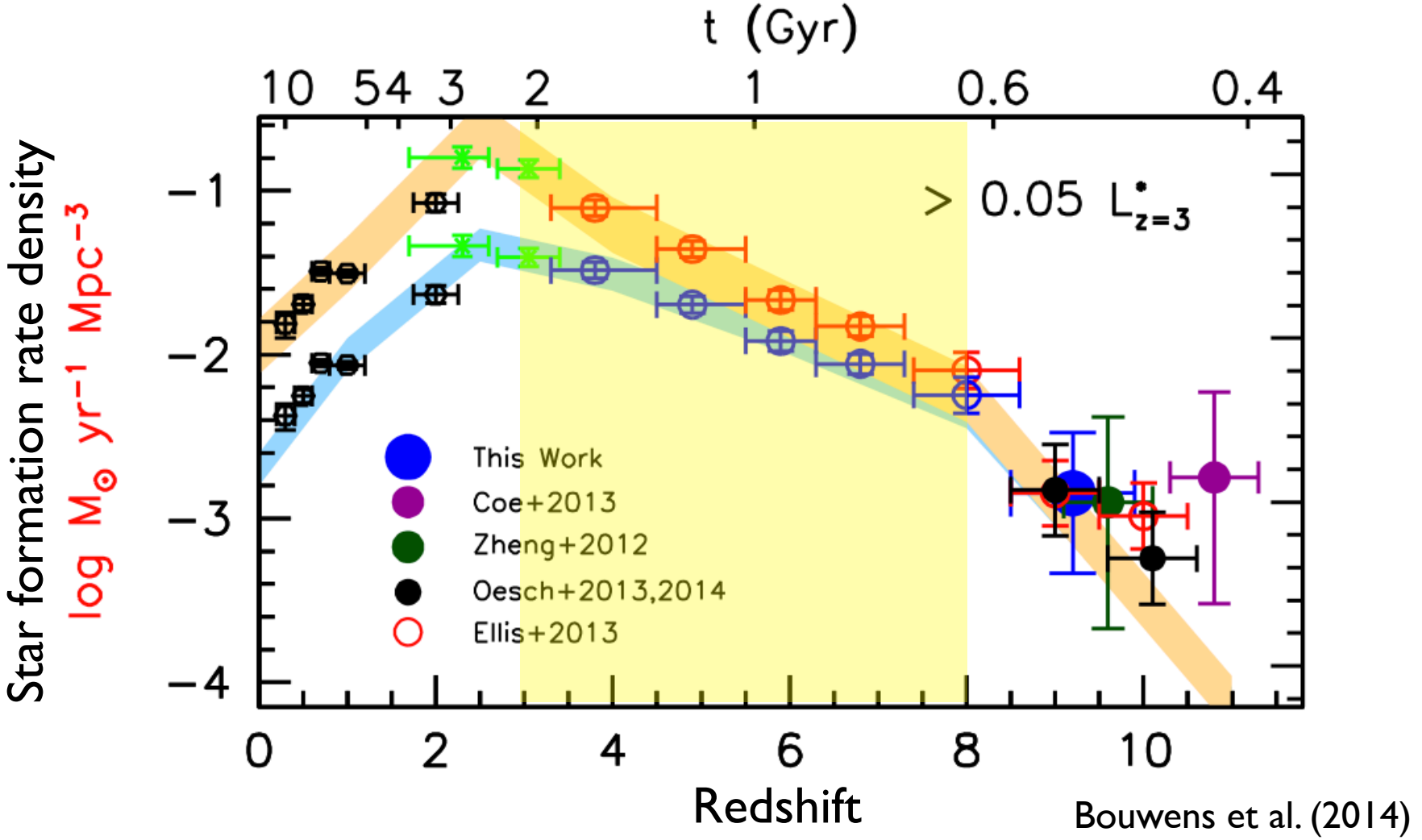

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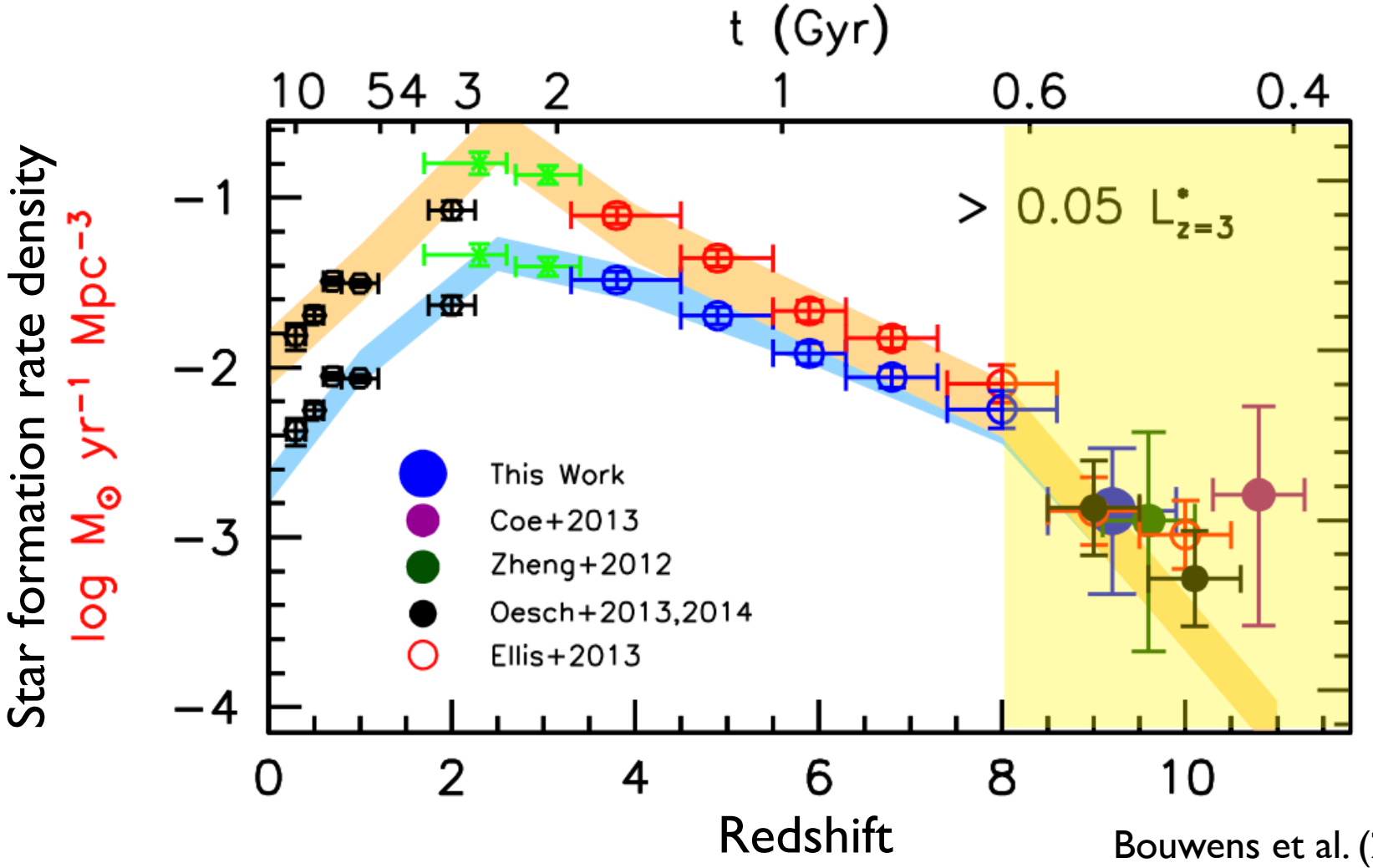

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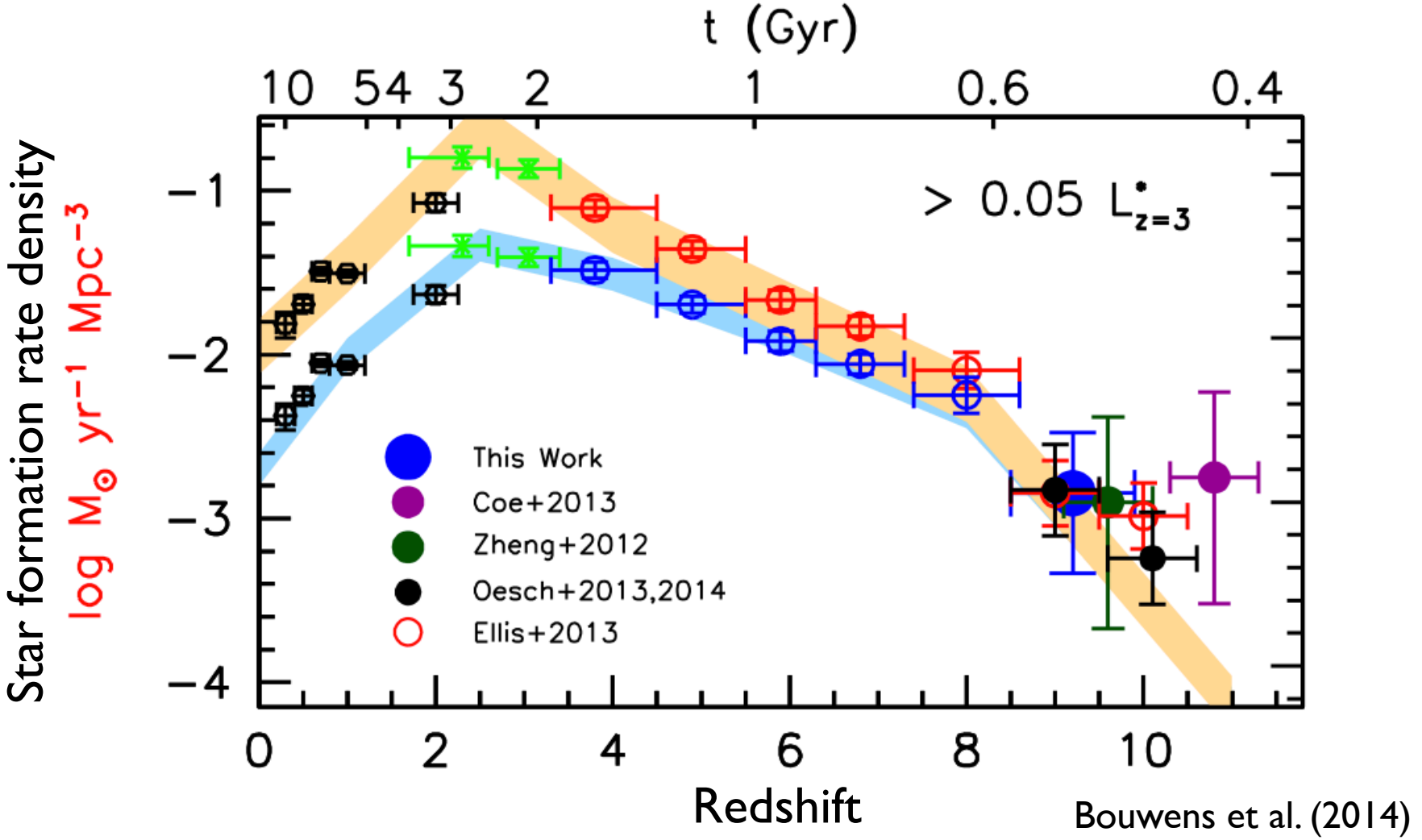
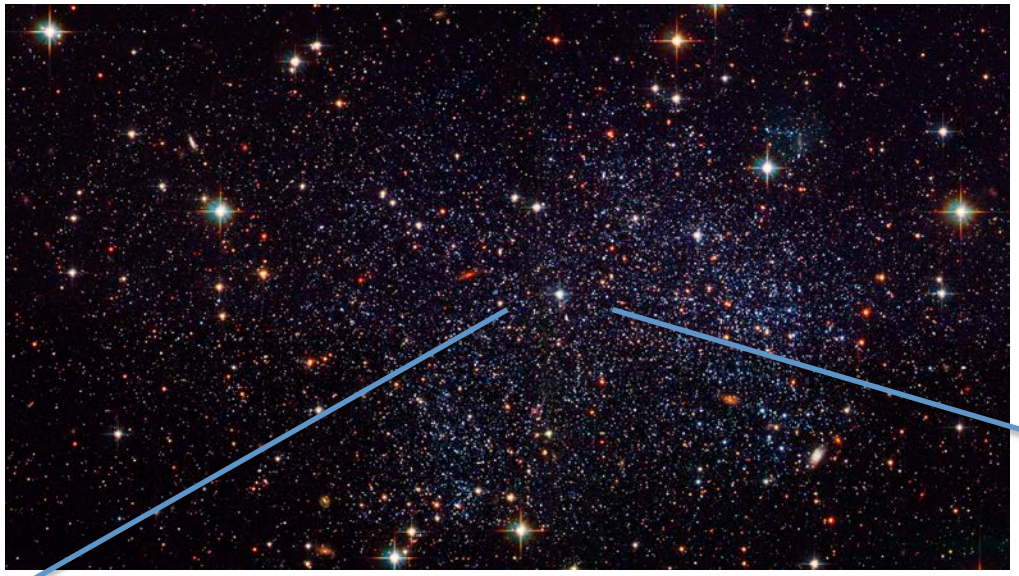


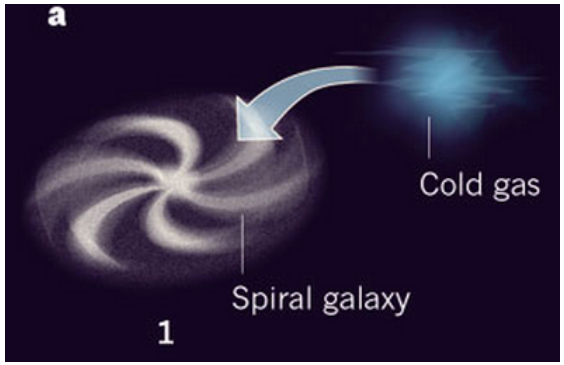
Bouwens et al. (2014)

A complex process

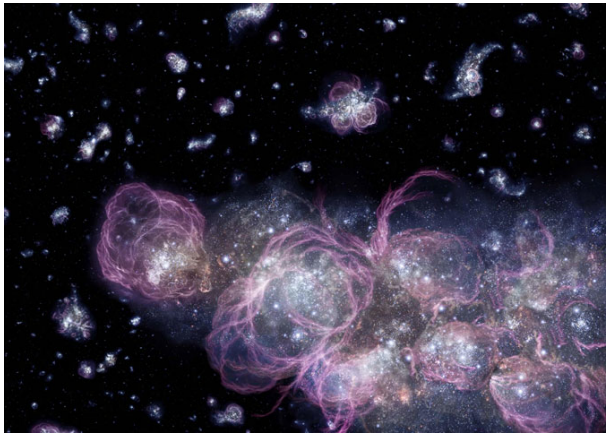


Much theoretical work!
E.g., Schaye et al. 2010, 2015; Booth & Schaye 2010; Dave et al. 2012; Haas et al. 2013; Feldmann 2013; Dekel et al. 2013; Altay et al. 2013; Lily et al. 2013; Sanchez Almeida et al. 2014; Furlong et al. 2014, etc …

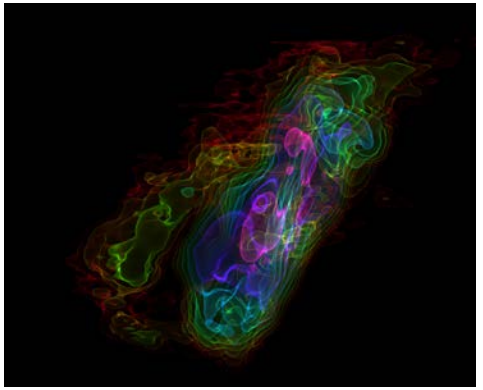
- Gas accretion



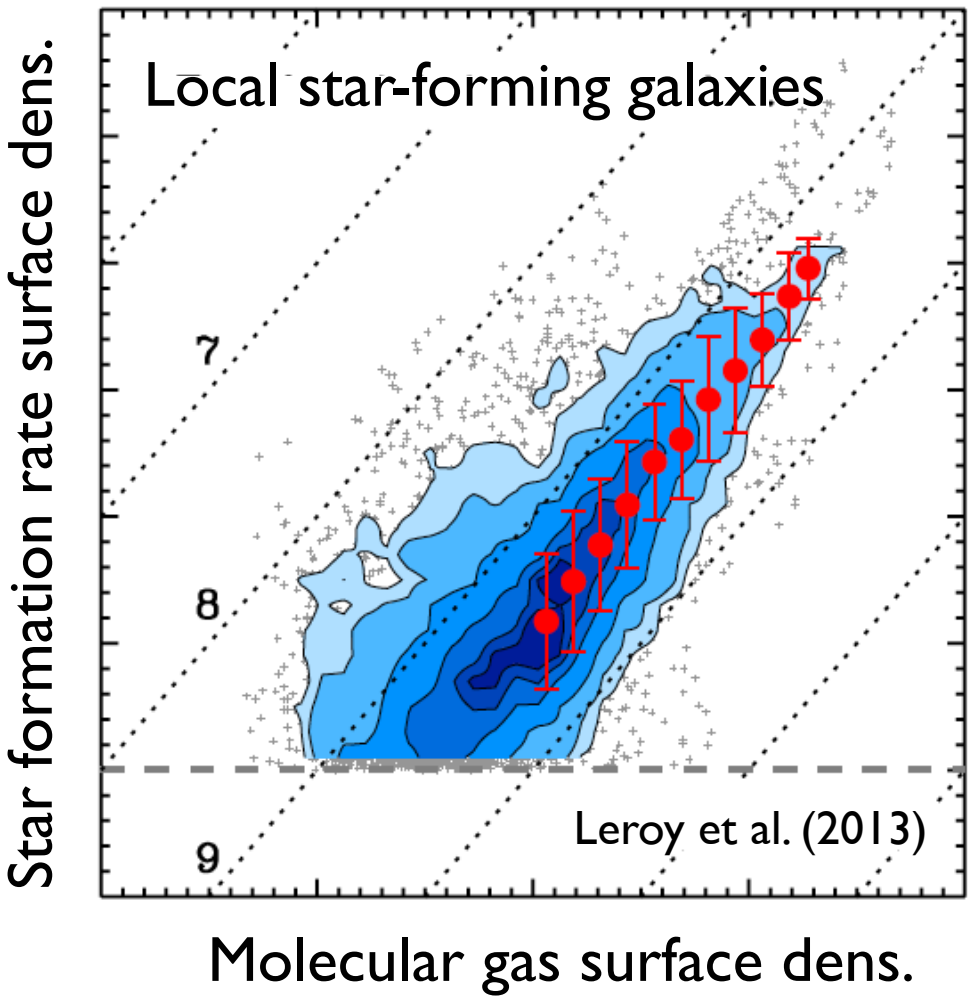
- Conversion into stars



- Feedback

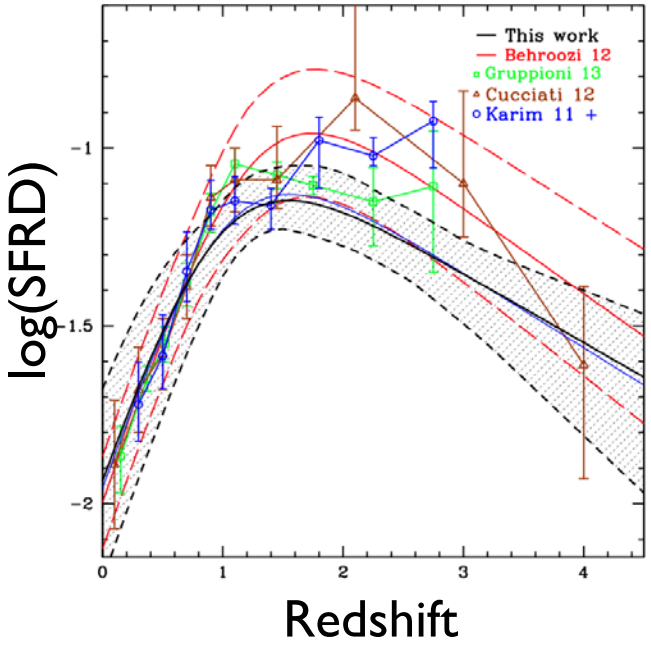


The star formation ‘law’

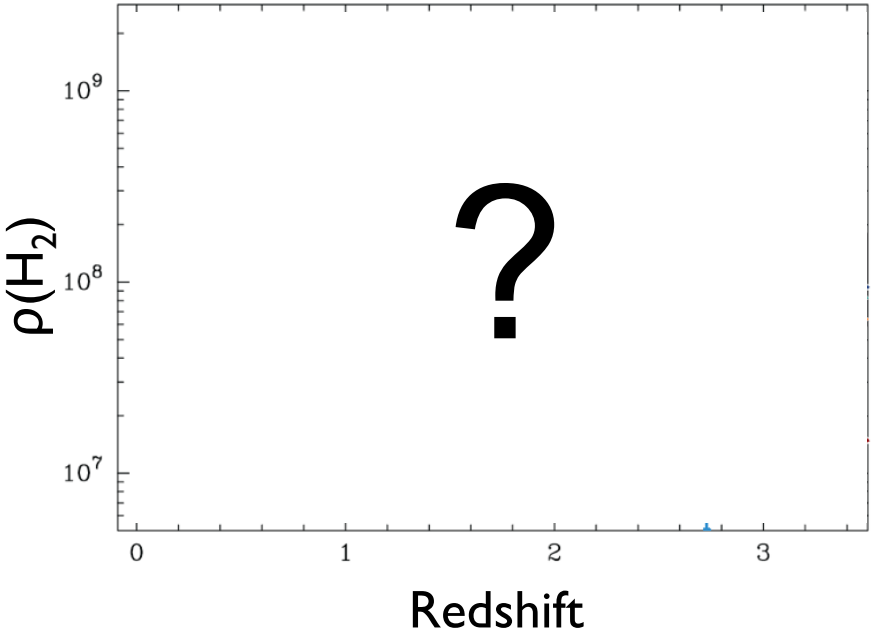


The cosmic molecular gas density

Ω(SFR)



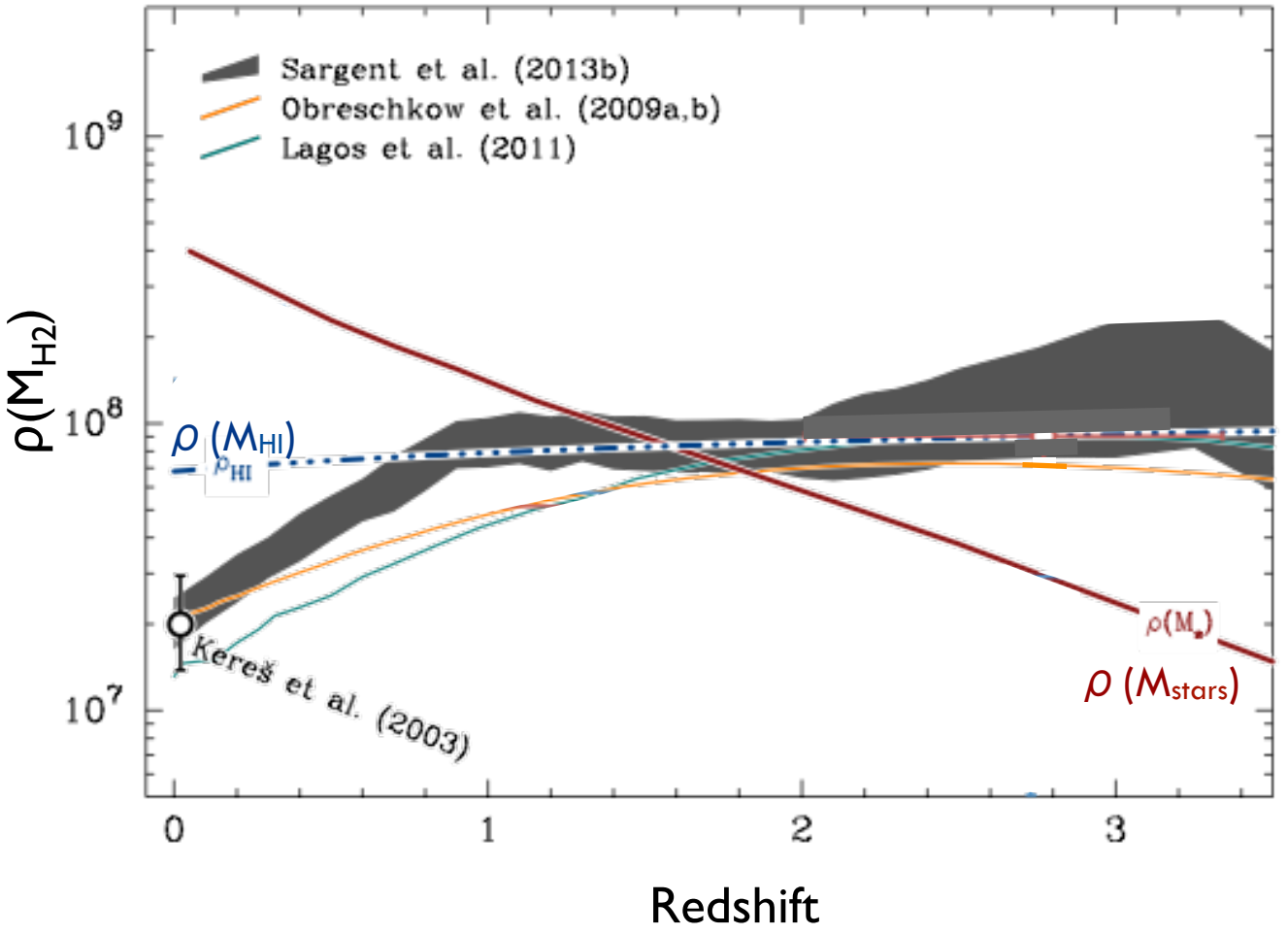
$\Omega(H_2)$



Ilbert et al. (2013)

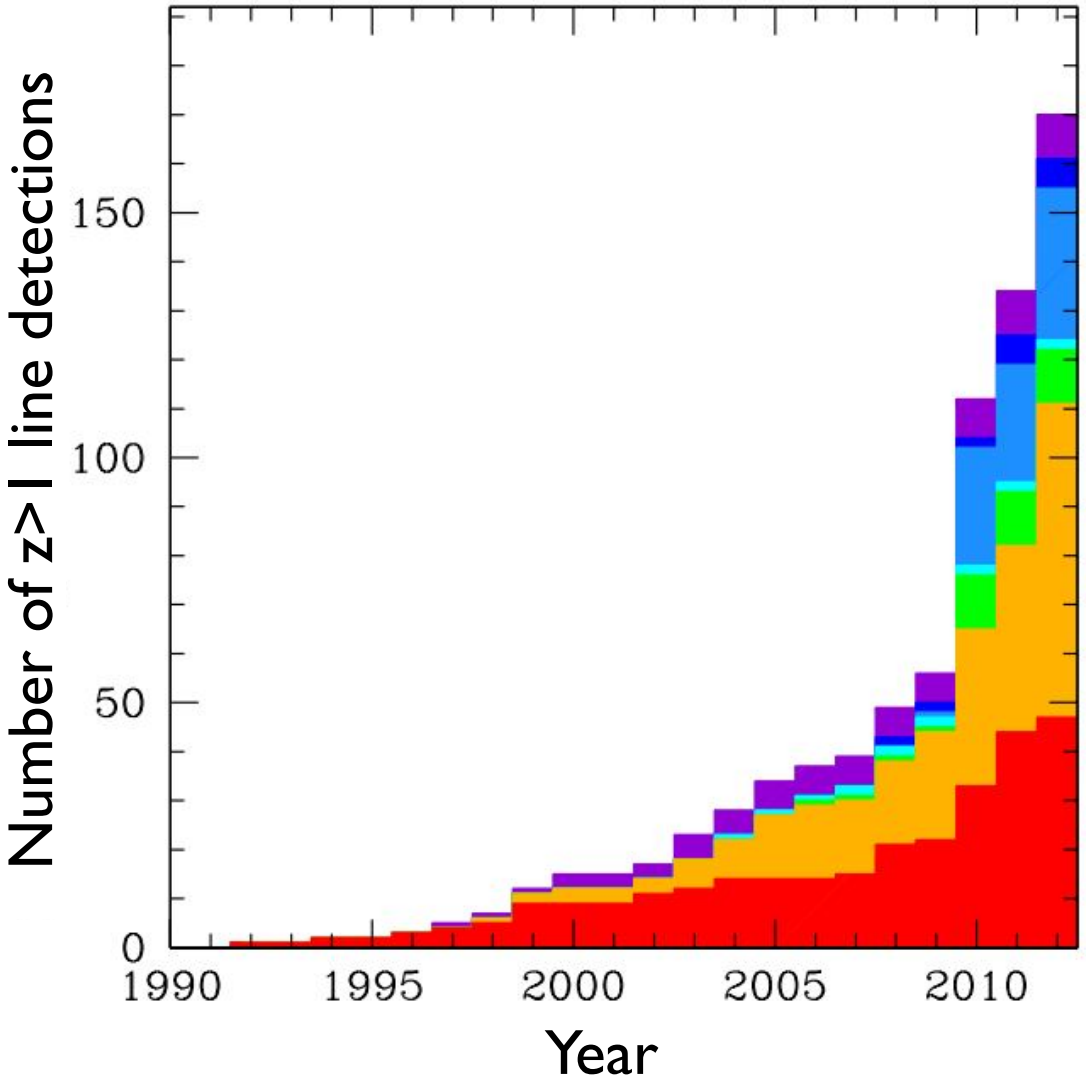
Predictions: H_2 density

ρ (M_{H2}) predictions + densities of stars and HI



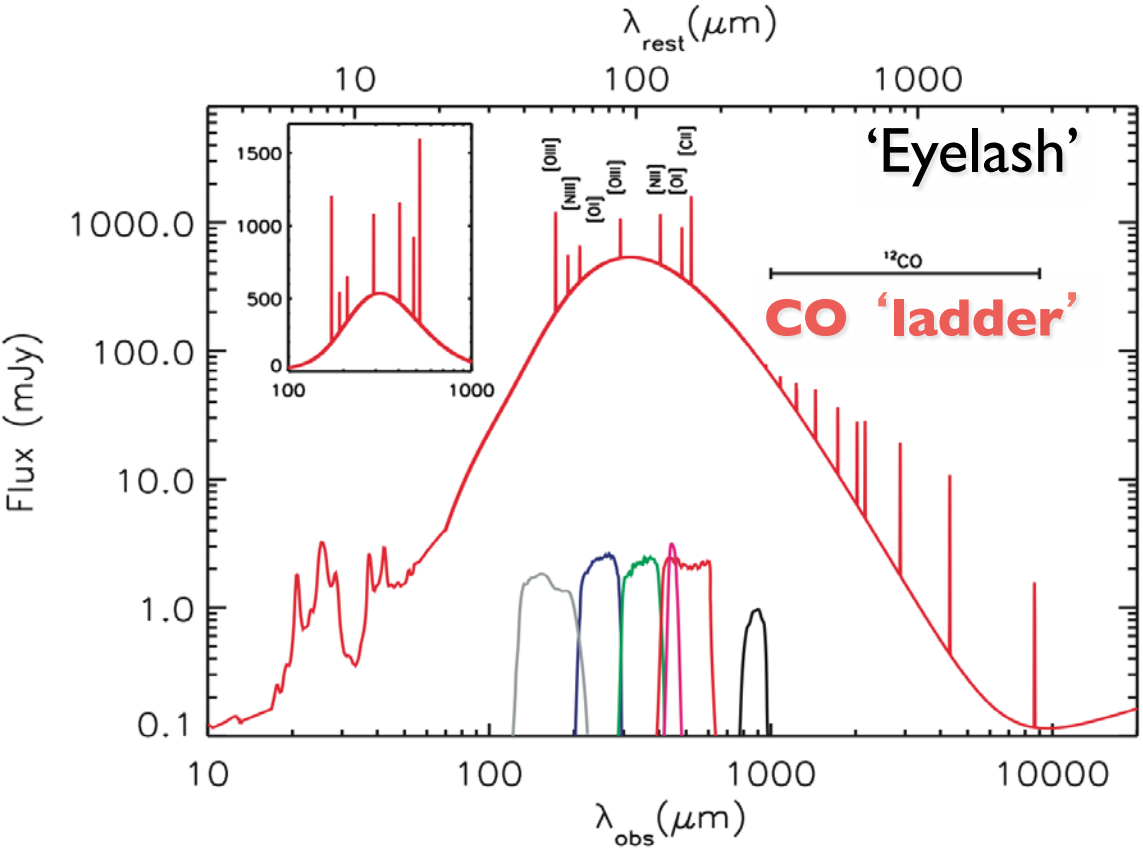
Sargent et al., in prep (based in Sargent et al. 2011, 2012)

High-z molecular gas detections



Carilli & Walter (2013)

Observing the molecular gas with CO

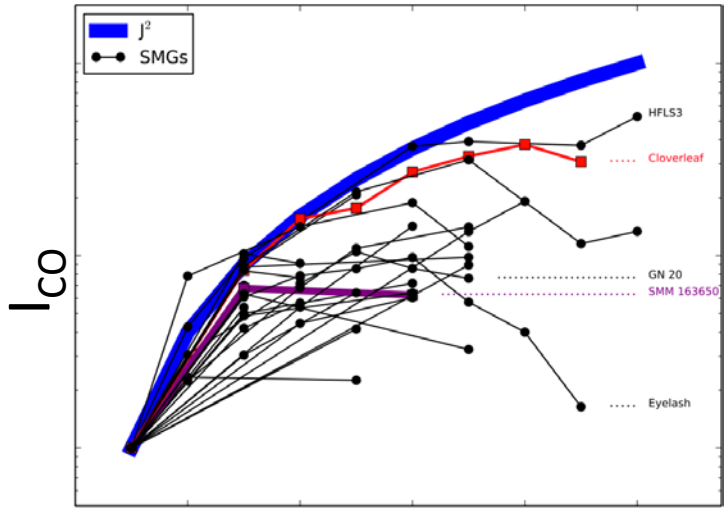


Smail et al. 2011
Swinbank et al. 2011

Requires knowledge of:

- α_{CO}
- Line ratios (excitation)

Narayanan et al. 2014



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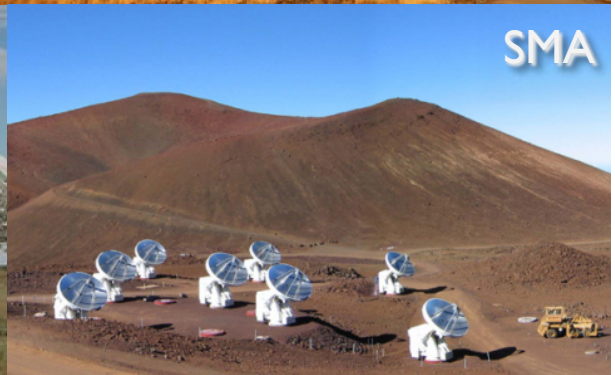

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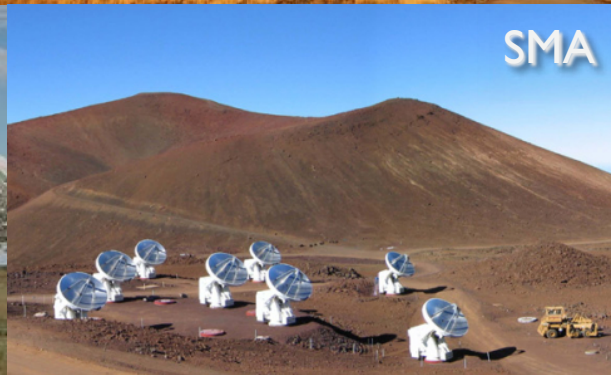

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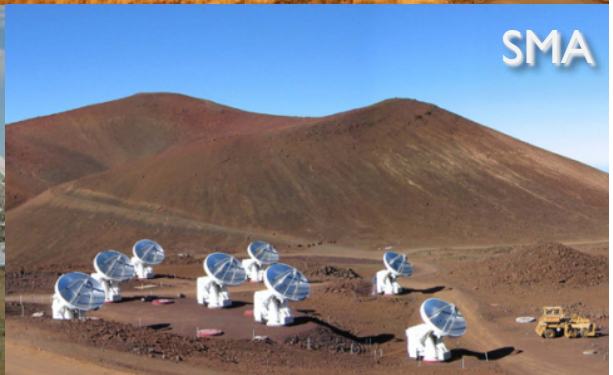

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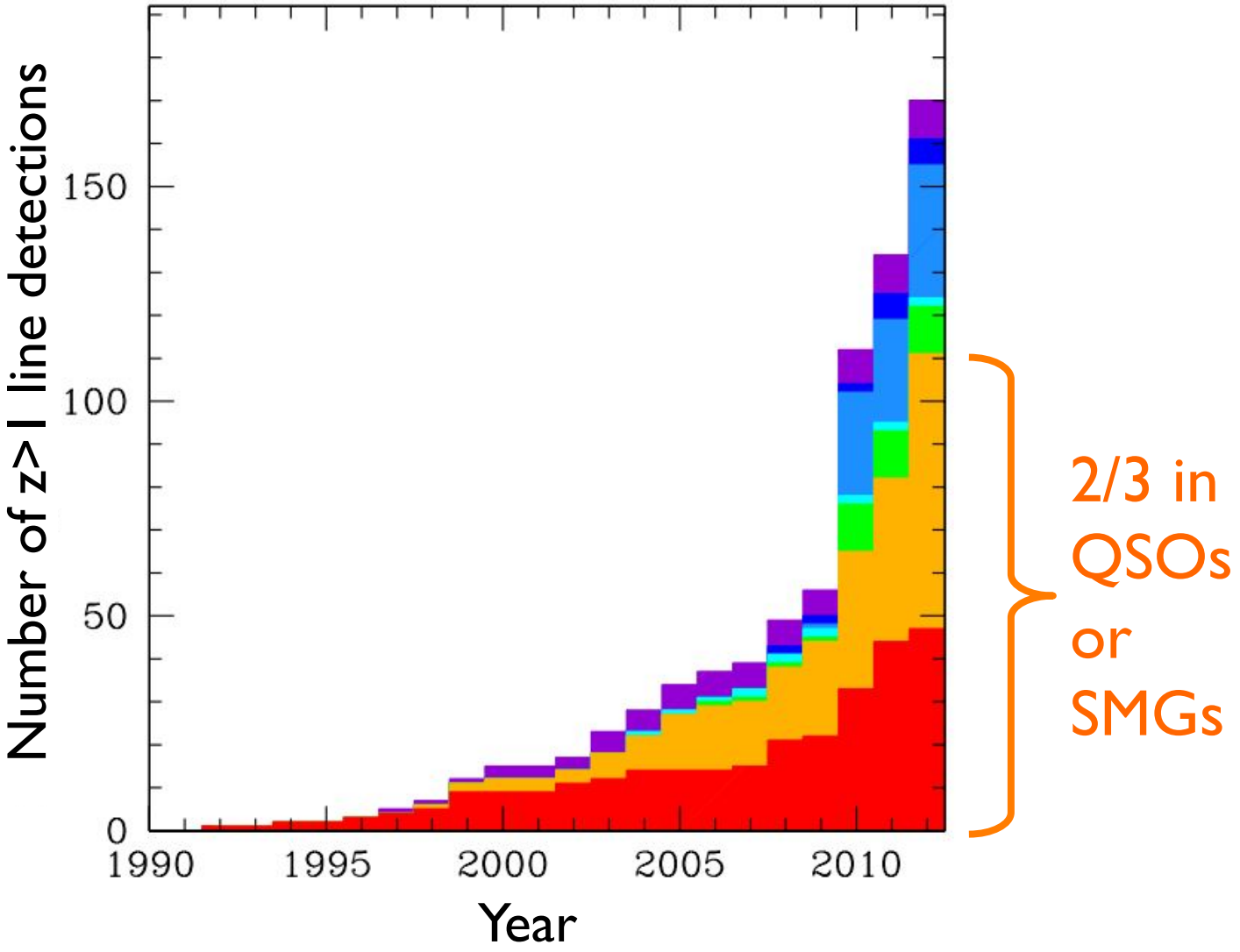
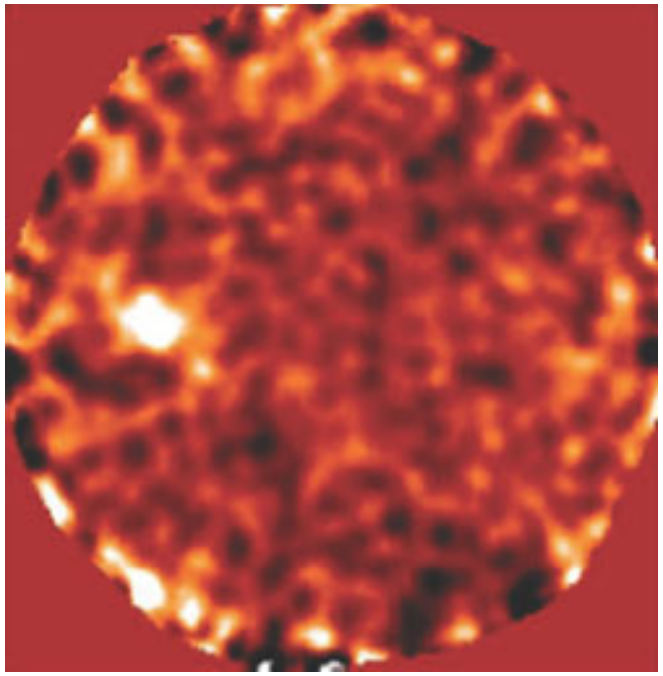


Carilli & Walter (2013)

Targeting FIR-bright starbursts

- Submillimeter galaxies (SMGs)
  - aka Dusty Star Forming Galaxies (DSFGs)
  - Starburst-dominated
  - SFRs $\geq$ 500-1000 $M_\odot$ yr^{-1}
  - Σ_{SFR} up to 1000 $M_\odot$ yr^{-1} kpc^{-2} ?!
  - Gas-rich

SCUBA 850μm



Barger et al. 1998

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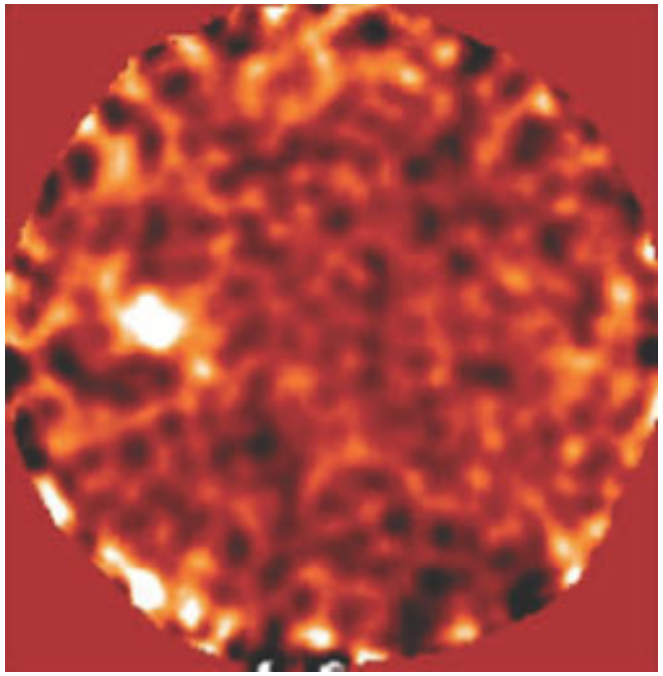


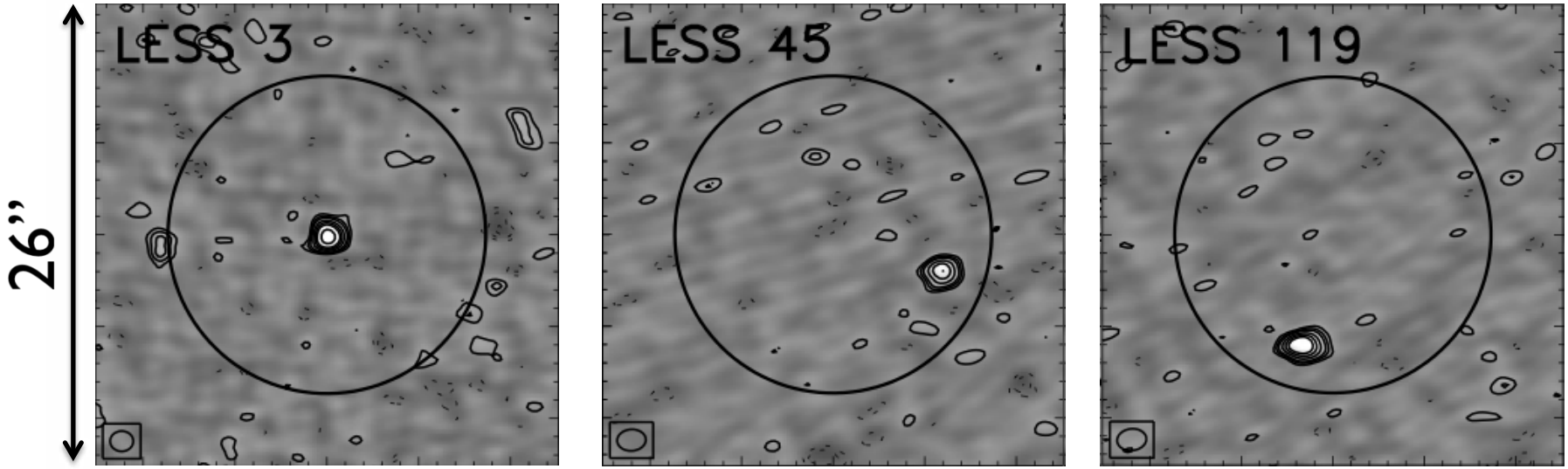
Barger et al. 1998

Complication: Difficult to identify counterpart, and thus redshift at which to go after the molecular line emission

ALMA LESS = 'ALESS'

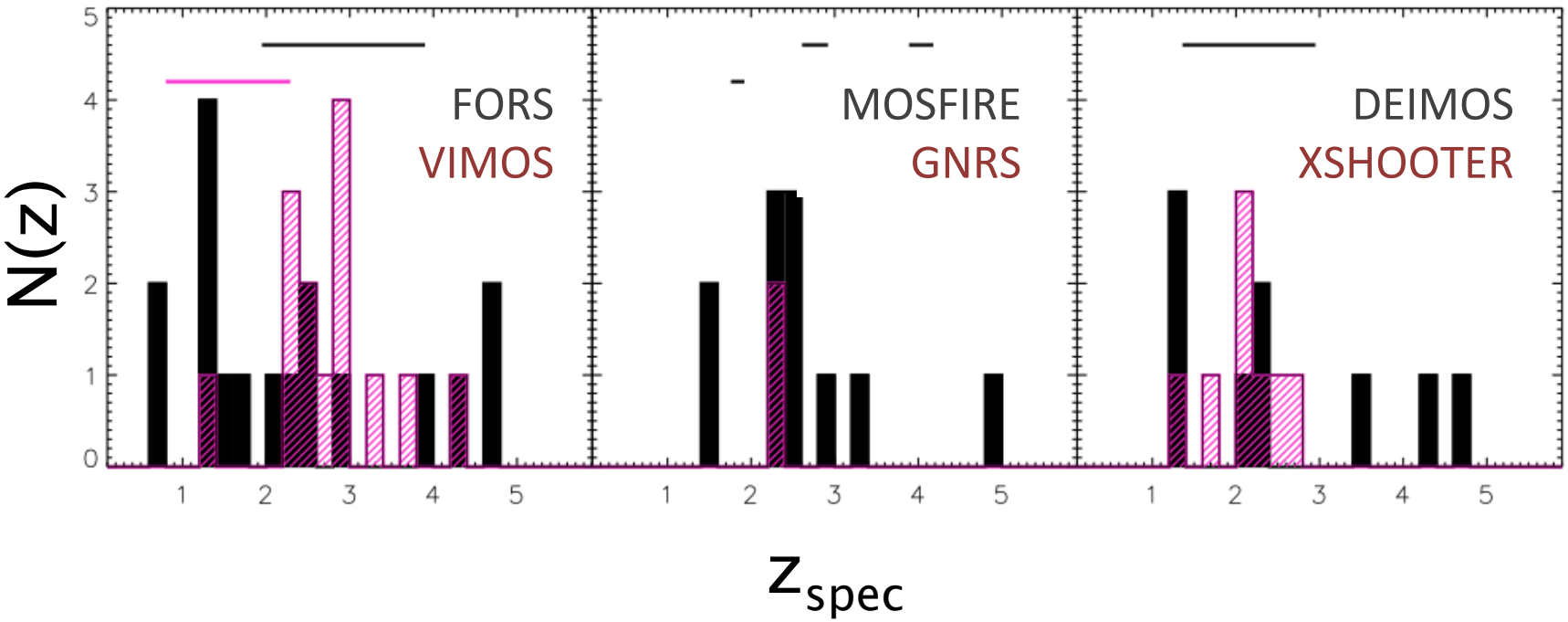
- We used Cycle 0 to map 126 LESS SMGs at 870μm (PI: Smail)
- Compact configuration ➔ 1.5" resolution (200× better!)
- 3× deeper than LESS in only 2min! (Hodge et al. 2013a; Karim et al. 2013)

Hodge et al. 2013a



Results of follow-up optical spectroscopy

Danielson et al. 2015 (in prep)



➔ Provides unambiguous counterparts for targeted CO observations

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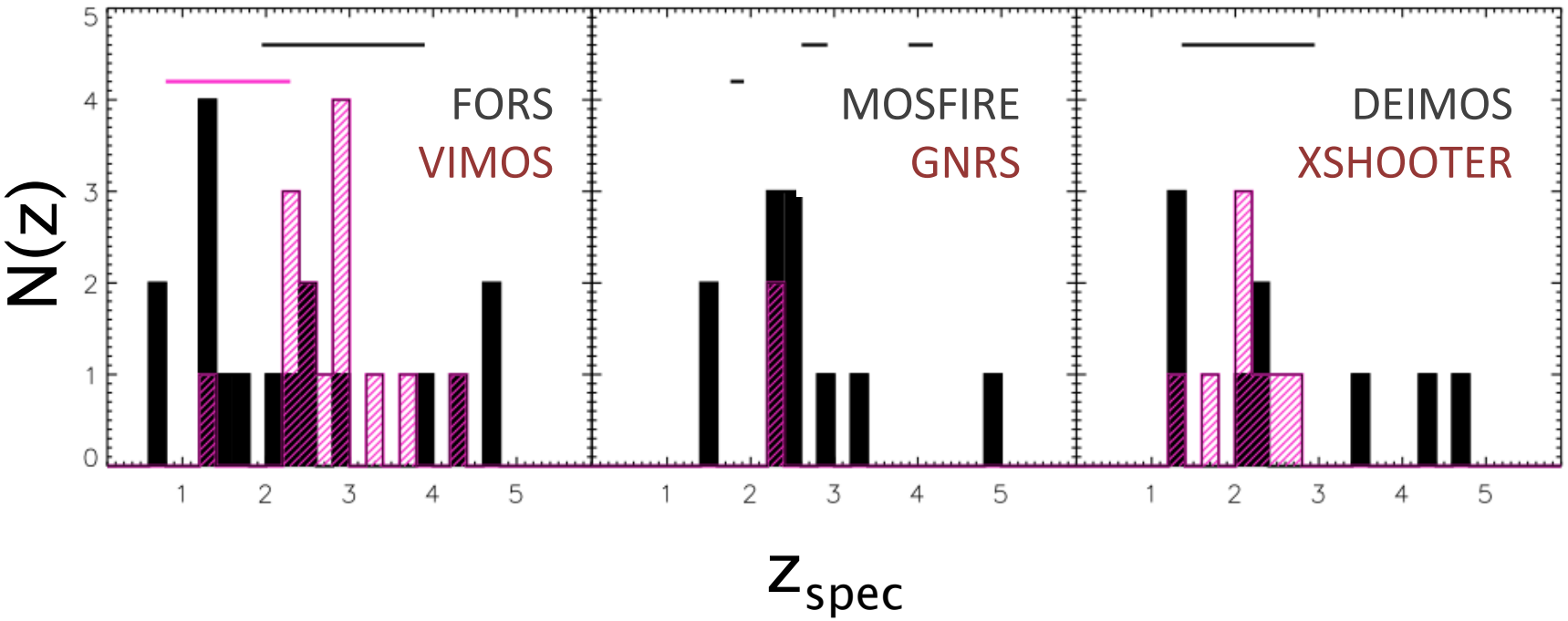
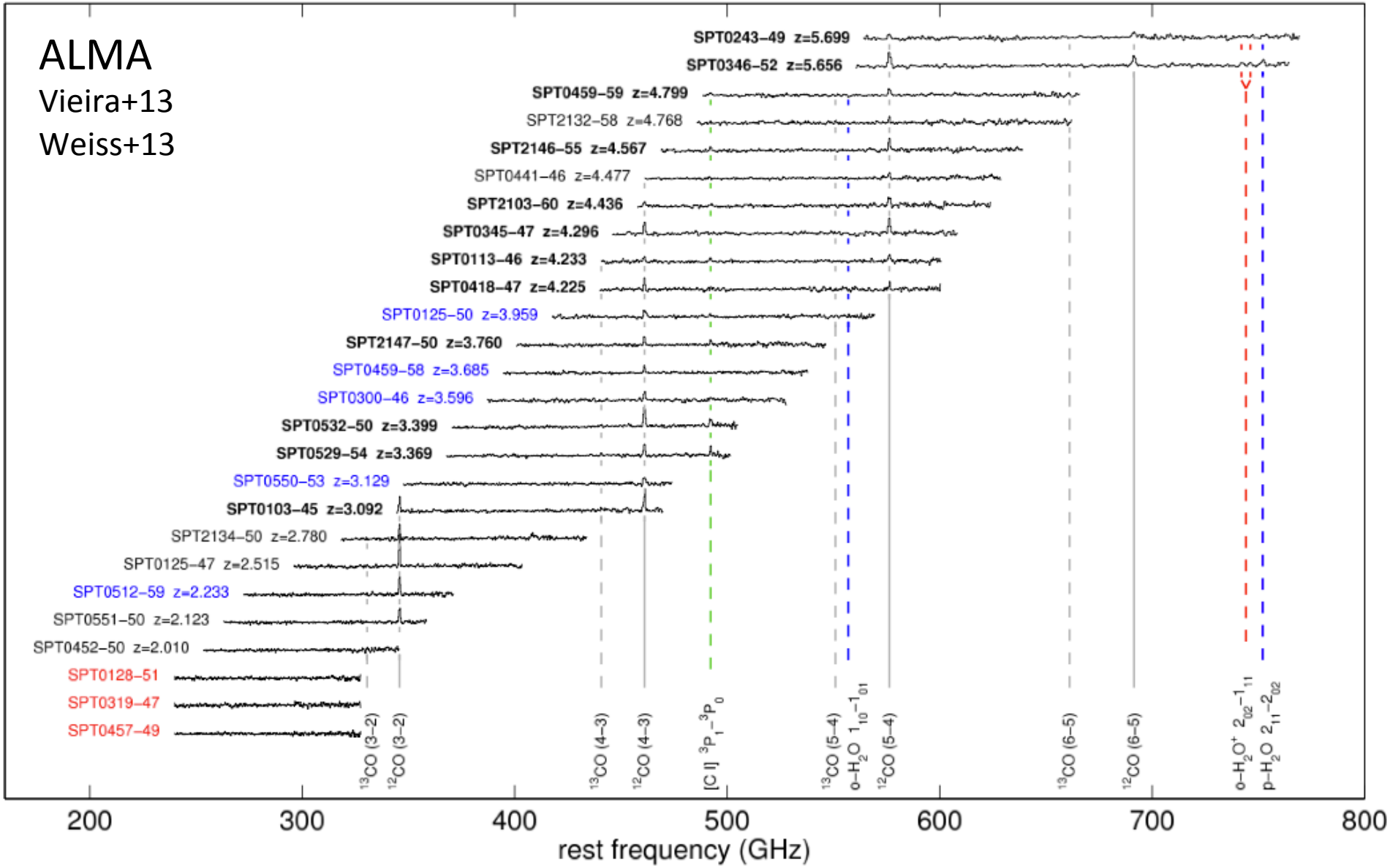


*__NOTE__: Redshifts only determined for 52/109 sources targeted…sources too faint in the optical!!

Blind line scans determine redshifts



High-resolution studies

Morphology / surface densities / kinematics / α_{CO} / excitation

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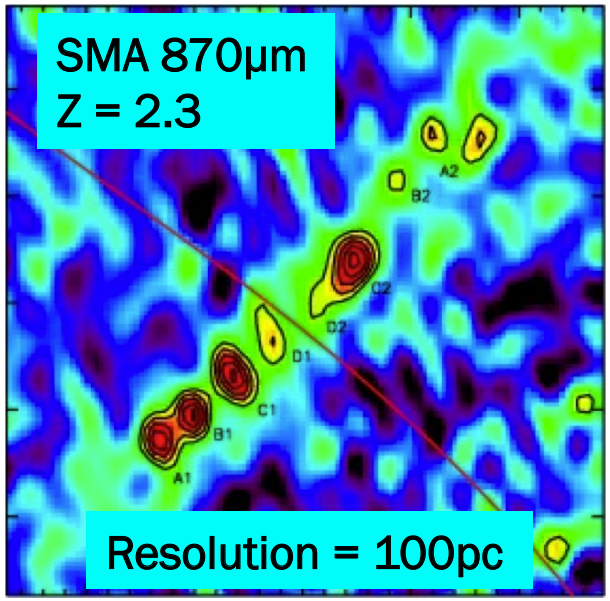
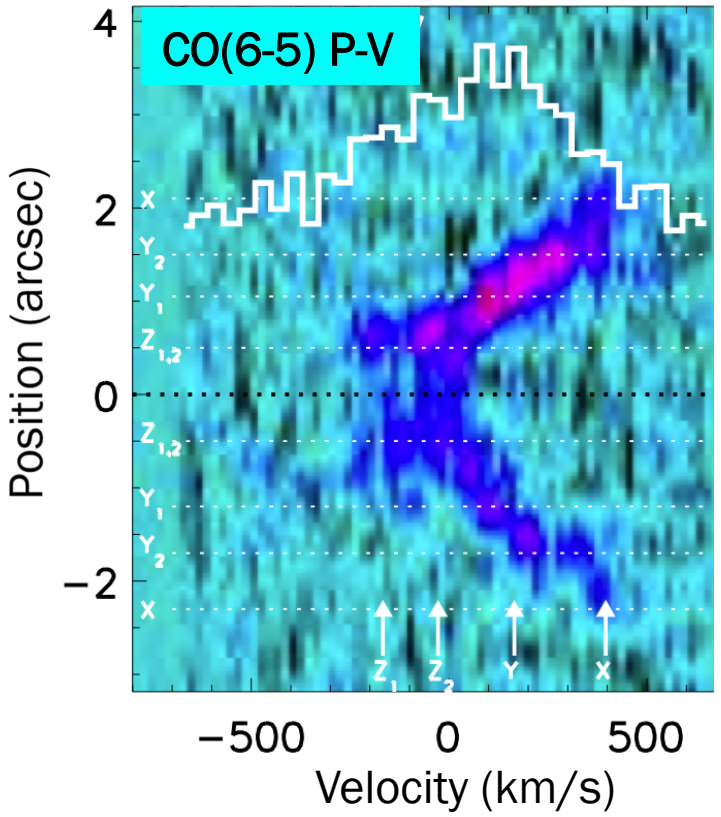
Morphology / surface densities / kinematics / α_{CO} / excitation

Example: Strongly-lensed 'Eyelash' galaxy (z~2.3)



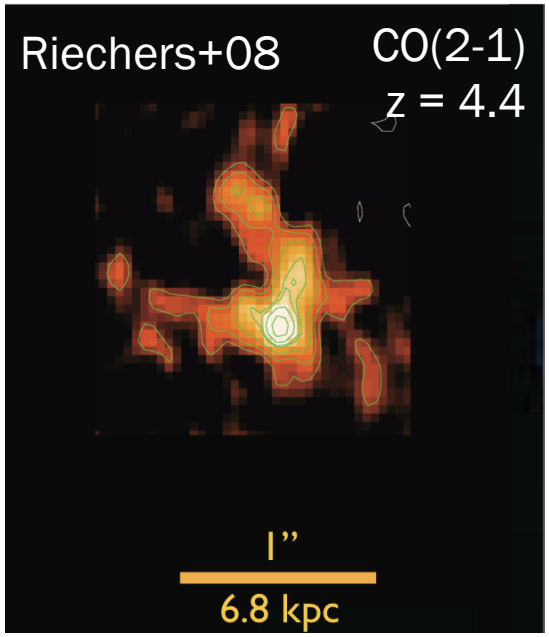


Swinbank et al. 2010, 2011; Danielson et al. 2012; Thomson et al. 2015

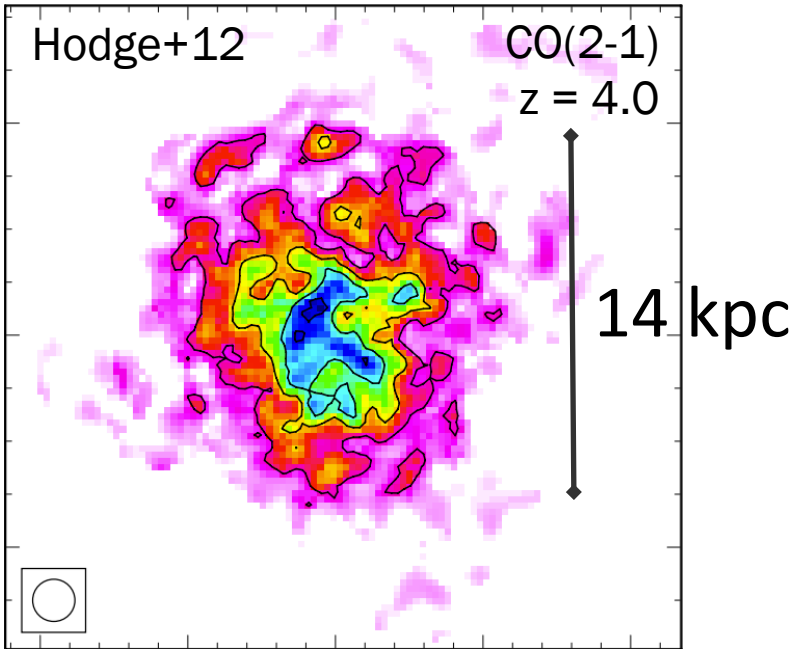
High-resolution studies

Morphology / surface densities / kinematics / α_{CO} / excitation

Example: QSO BRI 1335



Example: SMG GN20



Chaotic velocity field – late stage wet merger?

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Morphology / surface densities / kinematics / α_{CO} / excitation

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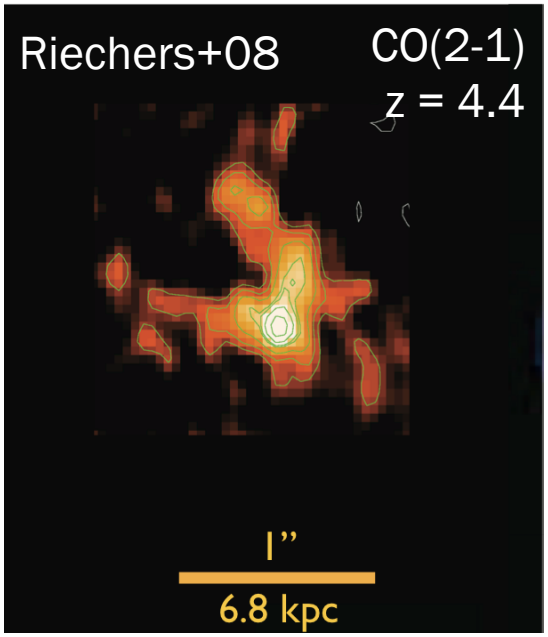

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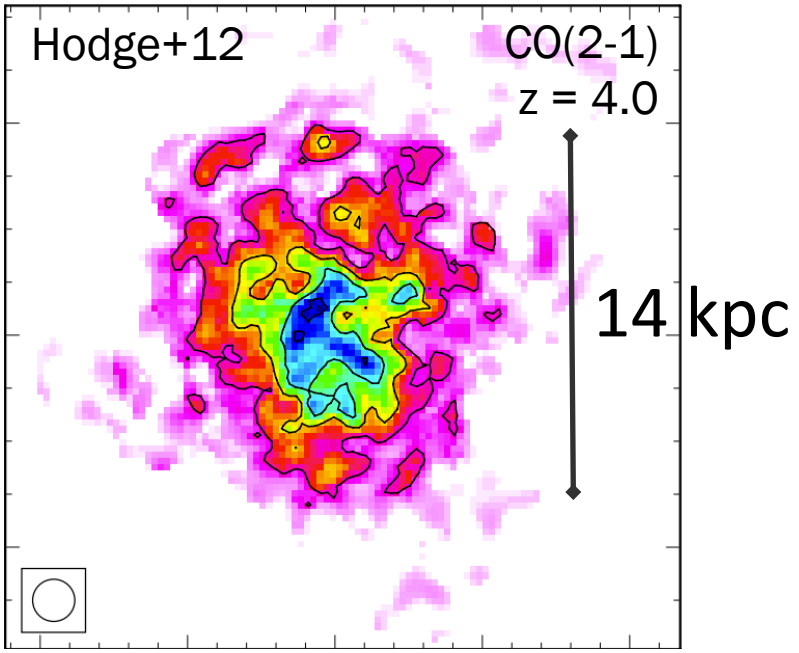
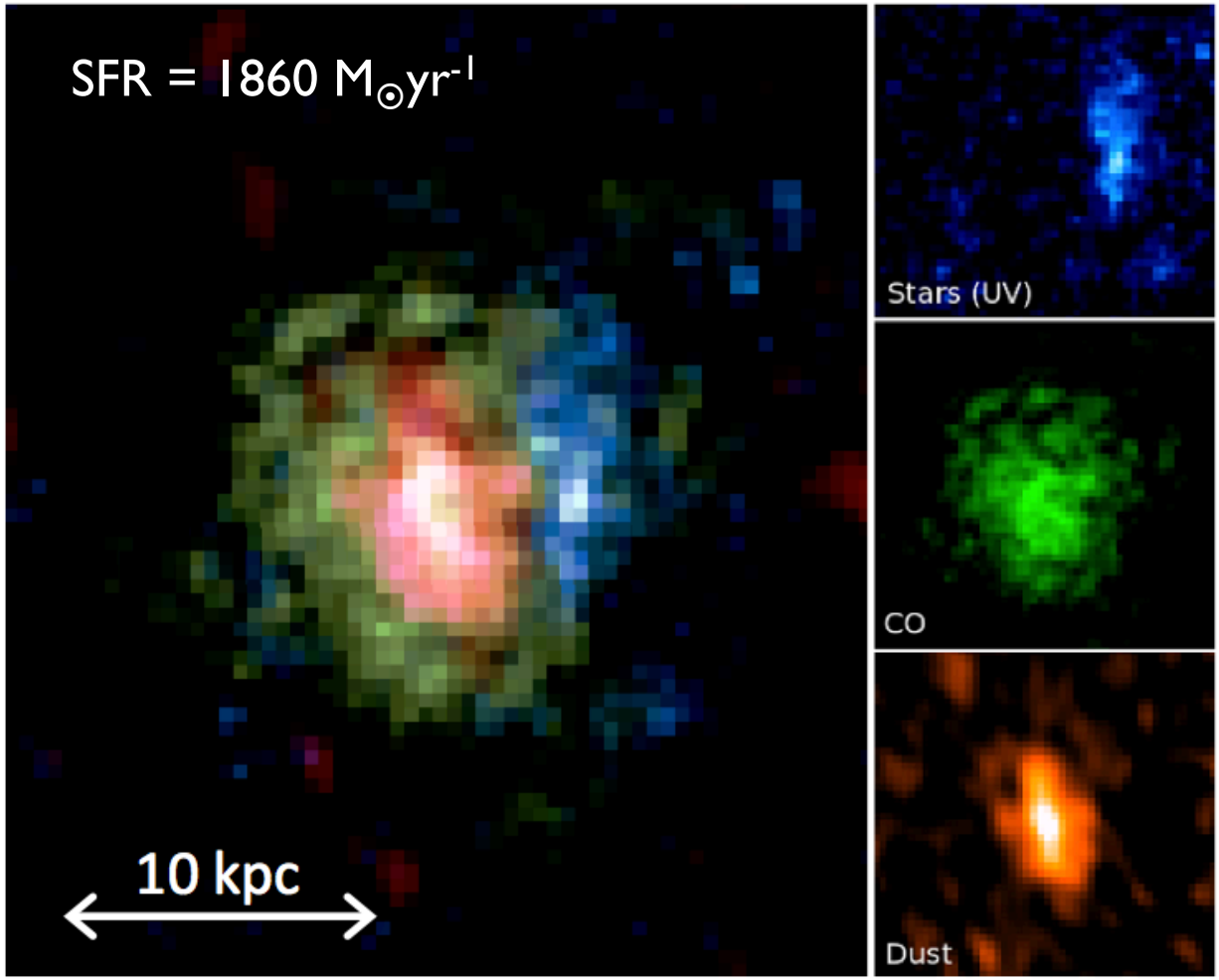


Extended, clumpy, rotating disk.
α_{CO} = 1.1, uniform gas excitation

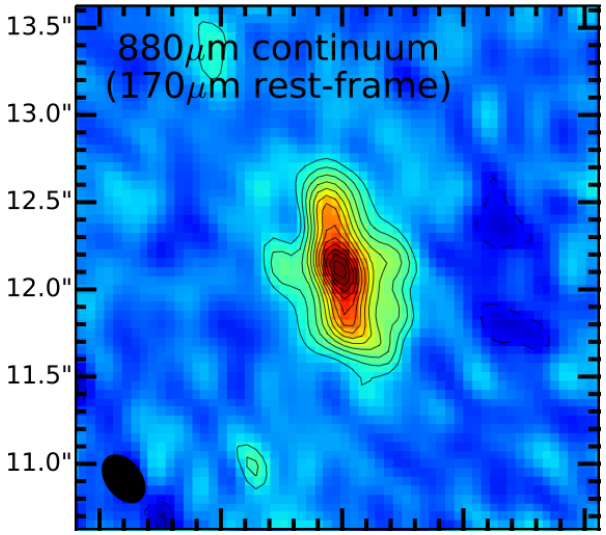
Gas-star formation comparison

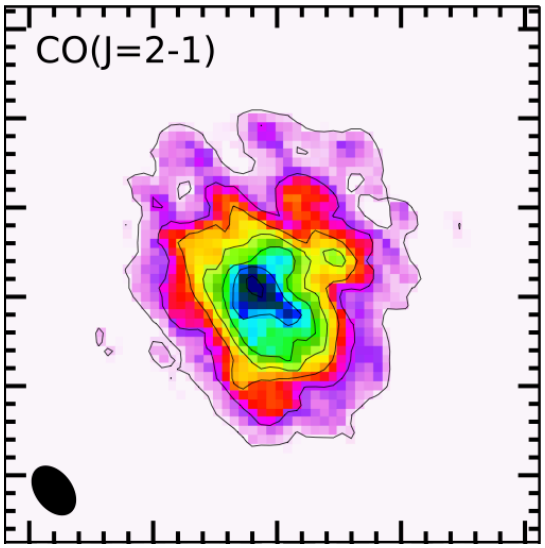
Gas-star formation comparison

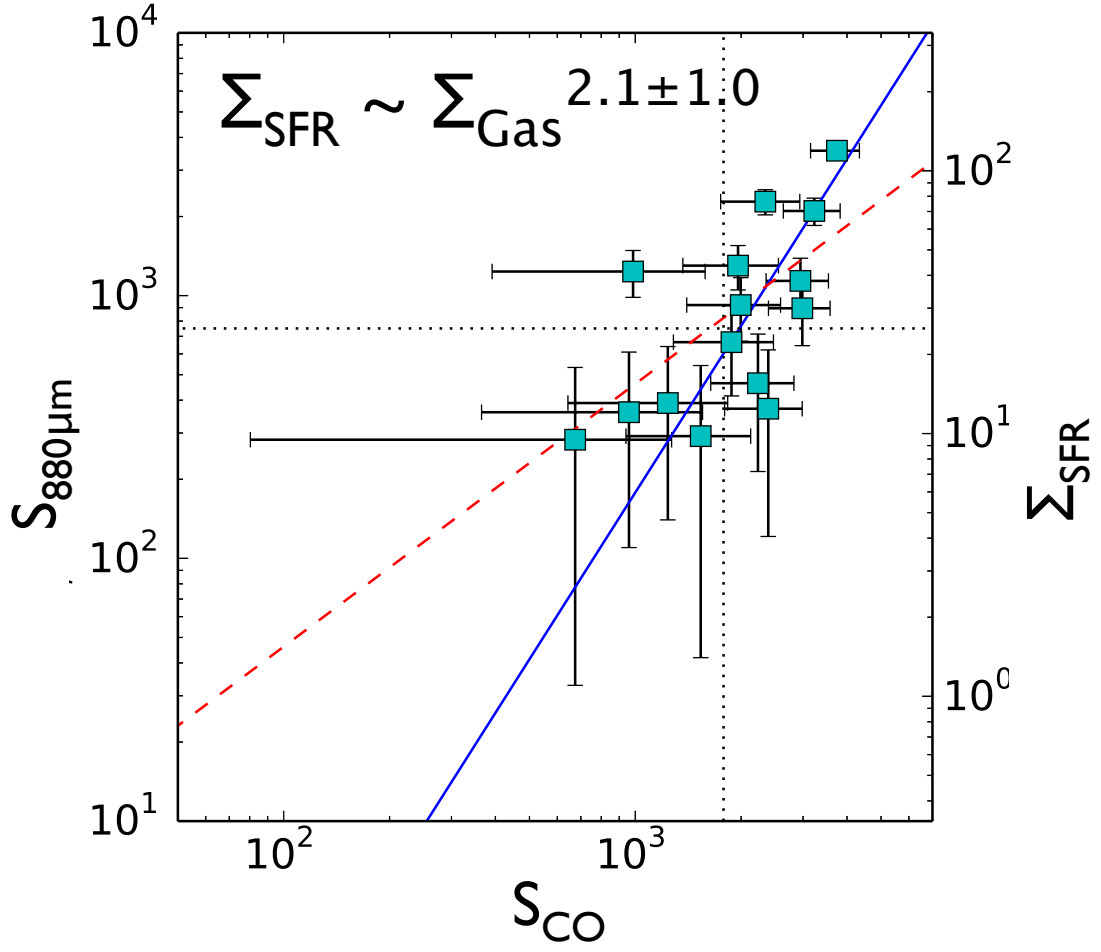


Hodge et al. (2015)

The resolved star formation law







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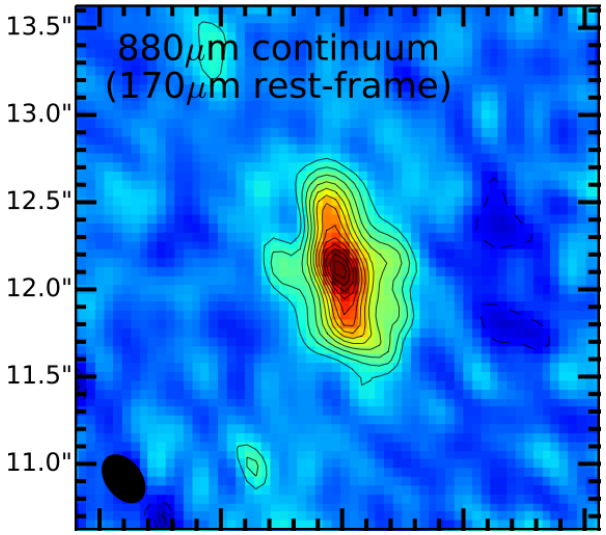
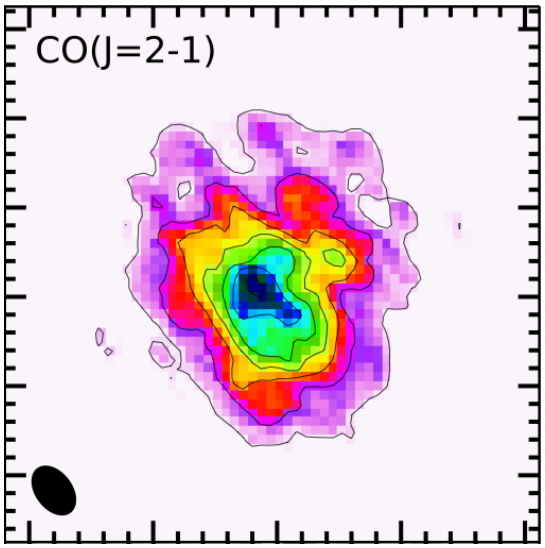
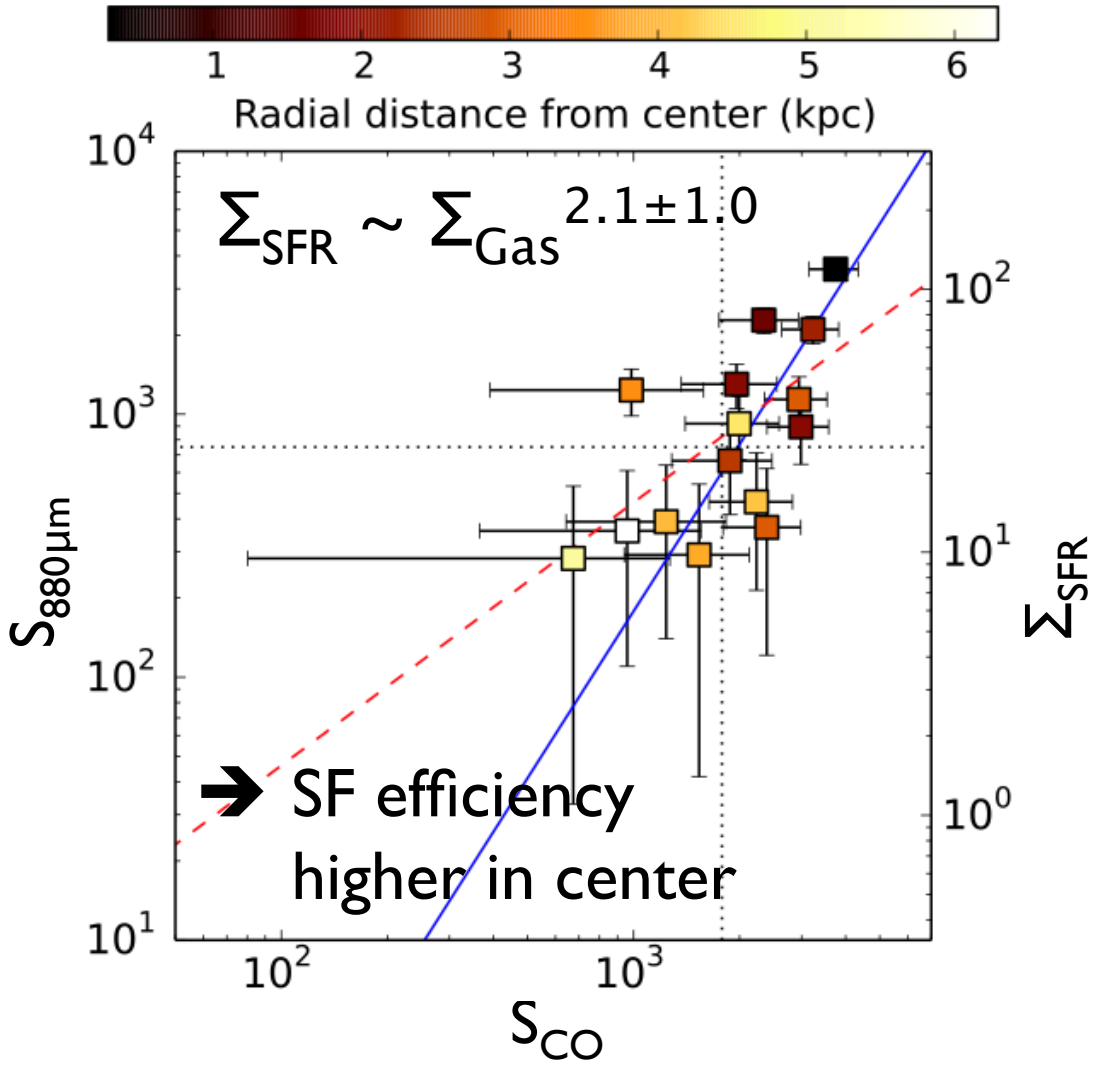






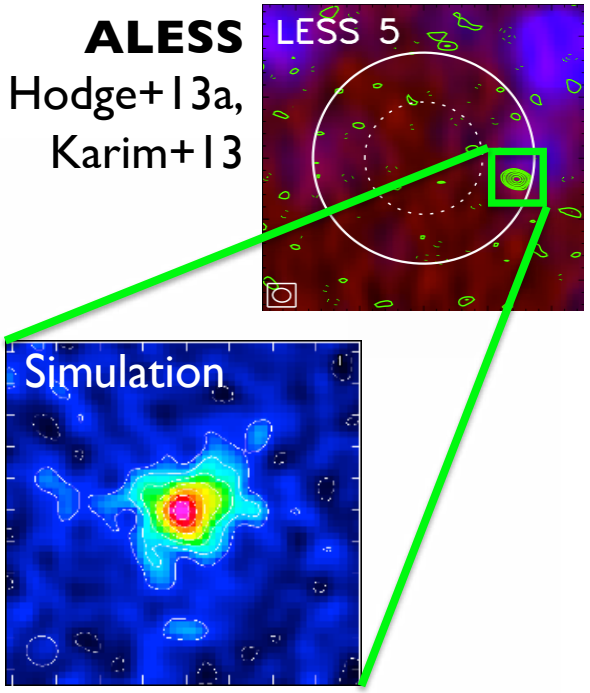
Hodge et al. (2015)

The future with ALMA:

Expanding the Sample

- Cycle 1 program (PI: Hodge): resolve 870μm continuum emission (~0.15”) in 15 ALESS SMGs
  - Morphology of obscured SF on ~1 kpc scales
  - Σ_{SFRs}
  - Nature of extreme starbursts (mergers/disks?)

ALESS
Hodge+13a,
Karim+13



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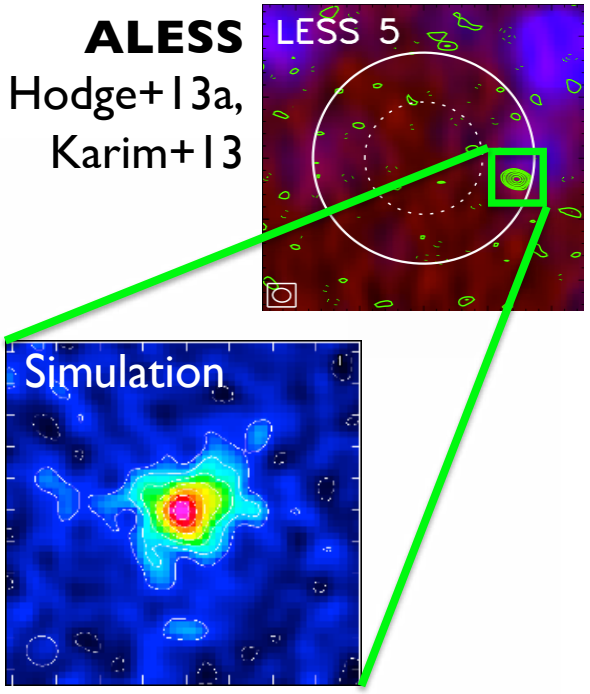

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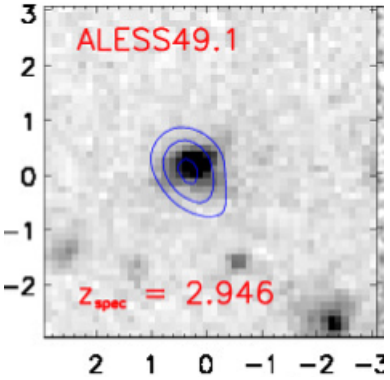
  - Nature of extreme starbursts (mergers/disks?)

- Cycle 2 program (PI: Hodge): matched-resolution (0.45") observations of CO(3-2), C+, and dust continuum in four z~2-3 ALESS SMGs
  - Gas masses, SF efficiencies, kinematics, PDR modeling
  - Spatially-resolved SF law on ~few kpc scales
  - Compare obscured/unobscured SF
  - Test correlation of C^+ with other SF tracers



ALMA 870μm contours (Hodge+13a) on HST/WFC3 (Swinbank+14)

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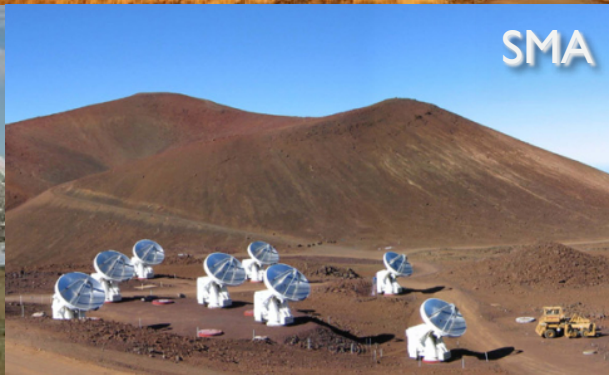

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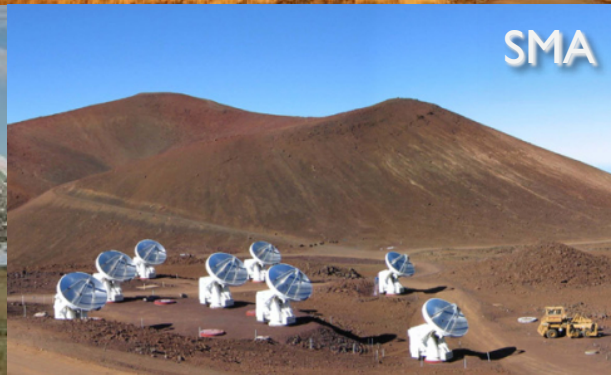
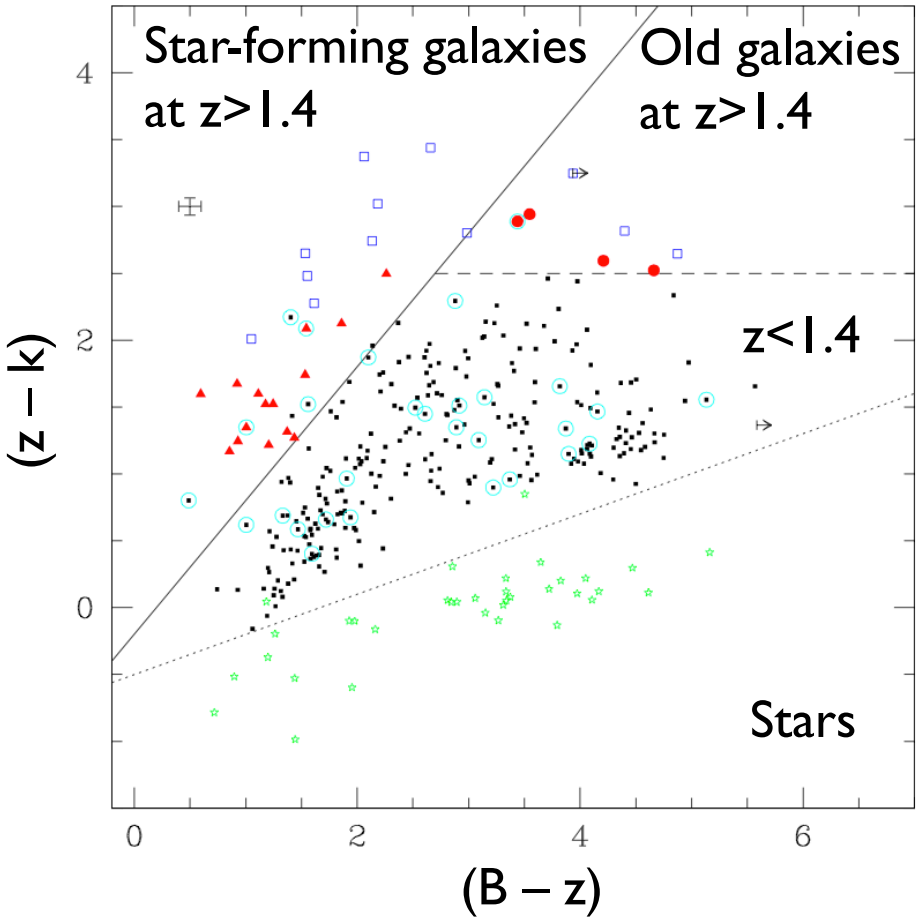


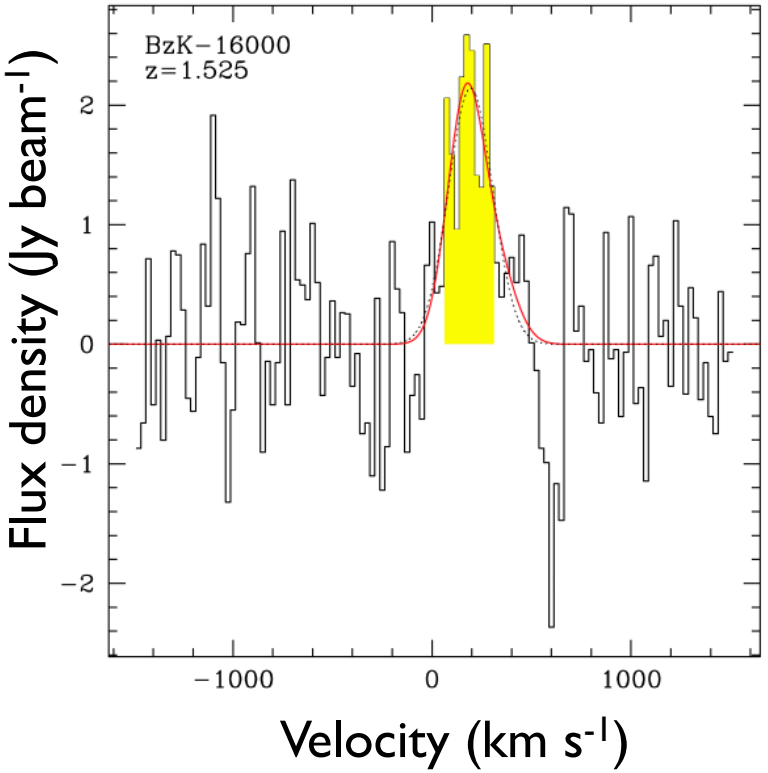
Color-selected galaxies (BzK, BM/BX)

e.g., BzK-selection

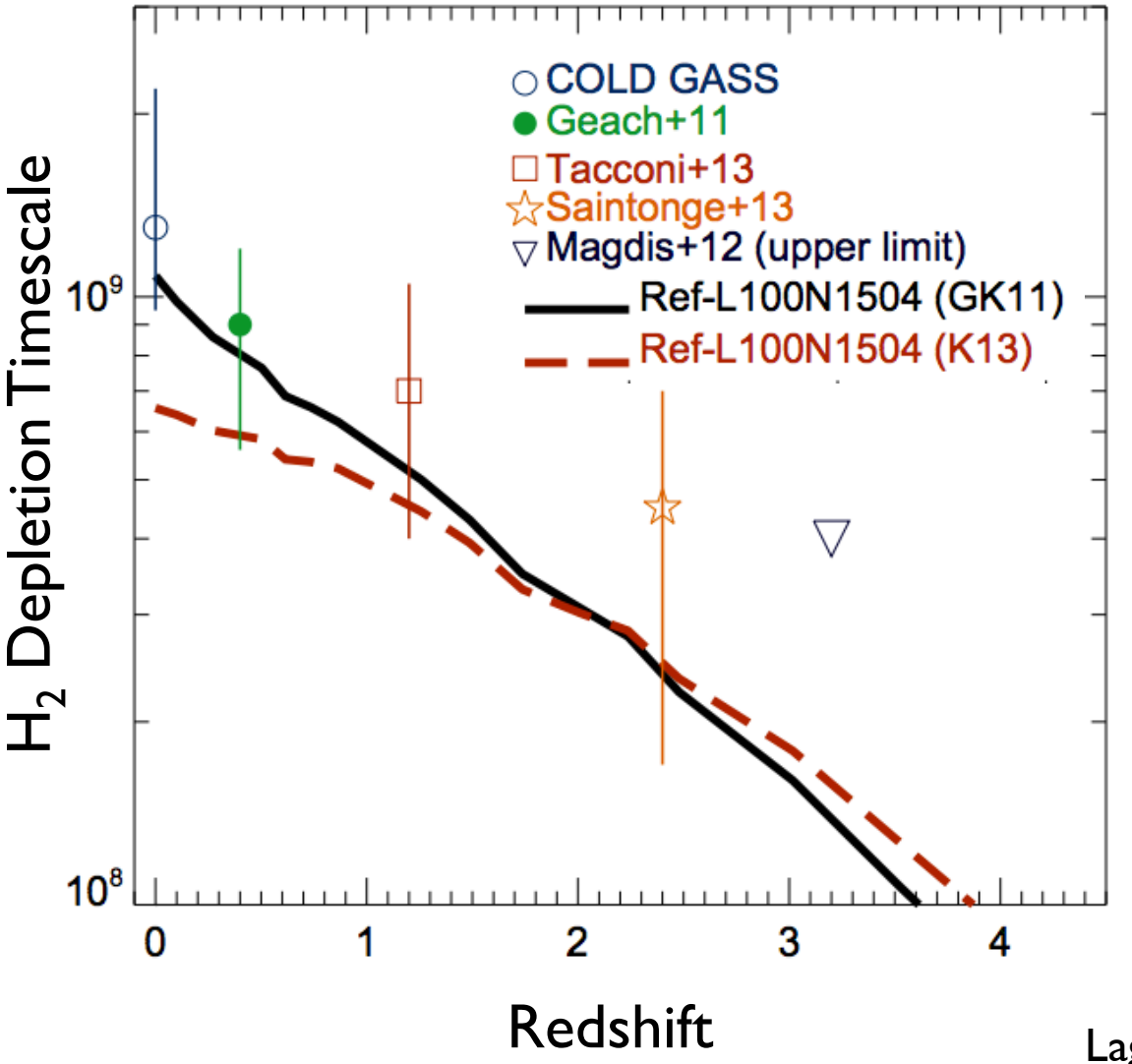


Daddi et al. (2004)

Daddi et al. (2010)

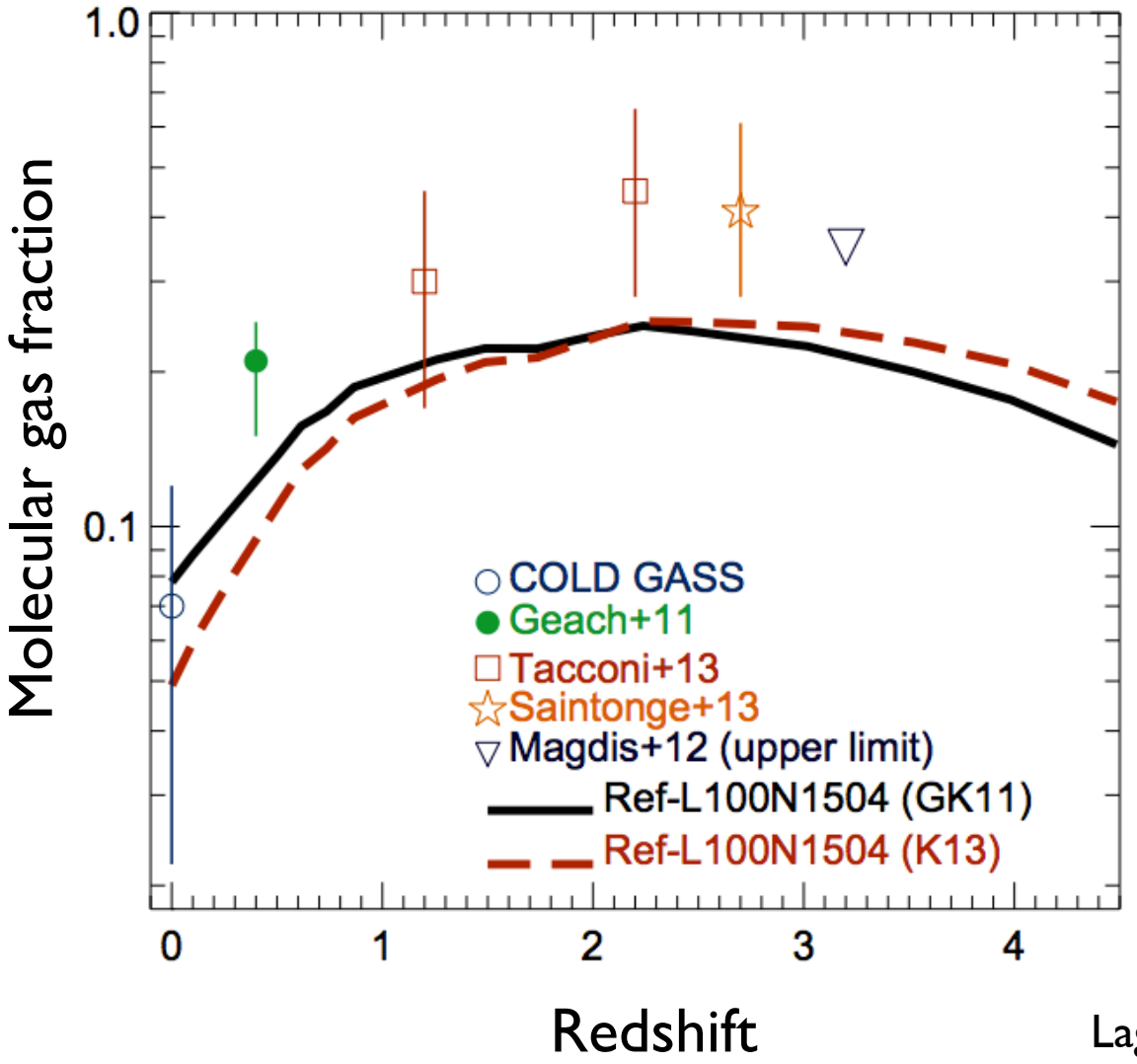


Depletion timescales decrease with z



Lagos et al. (2015)

Gas fractions increase out to z~2



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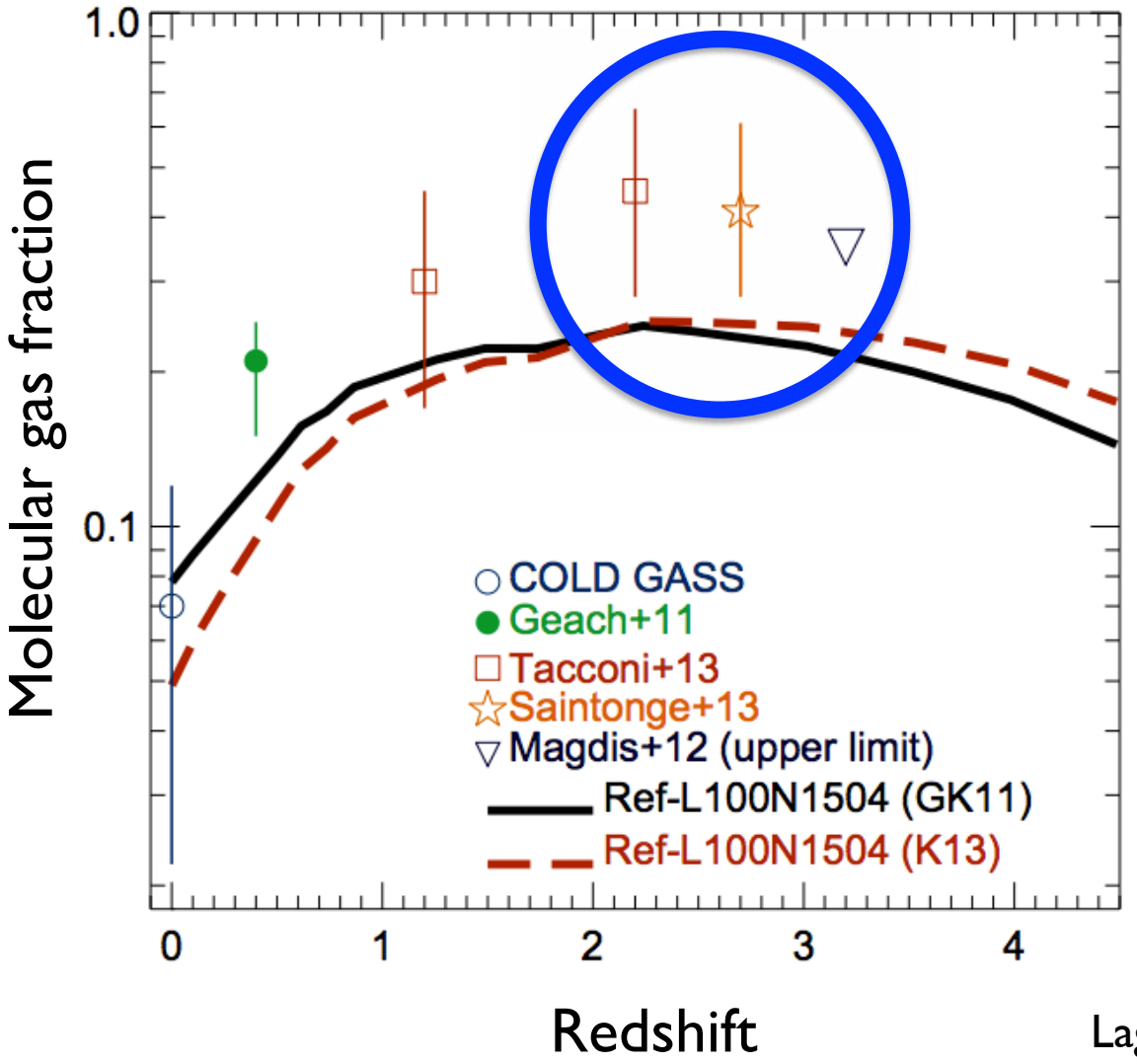

Lagos et al. (2015)

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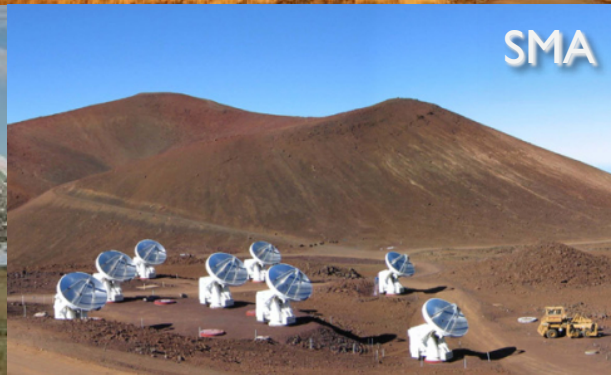

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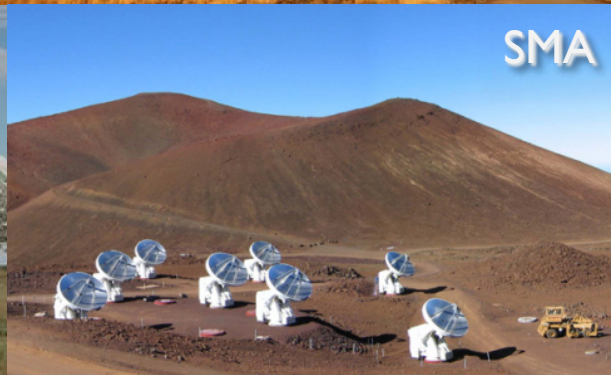
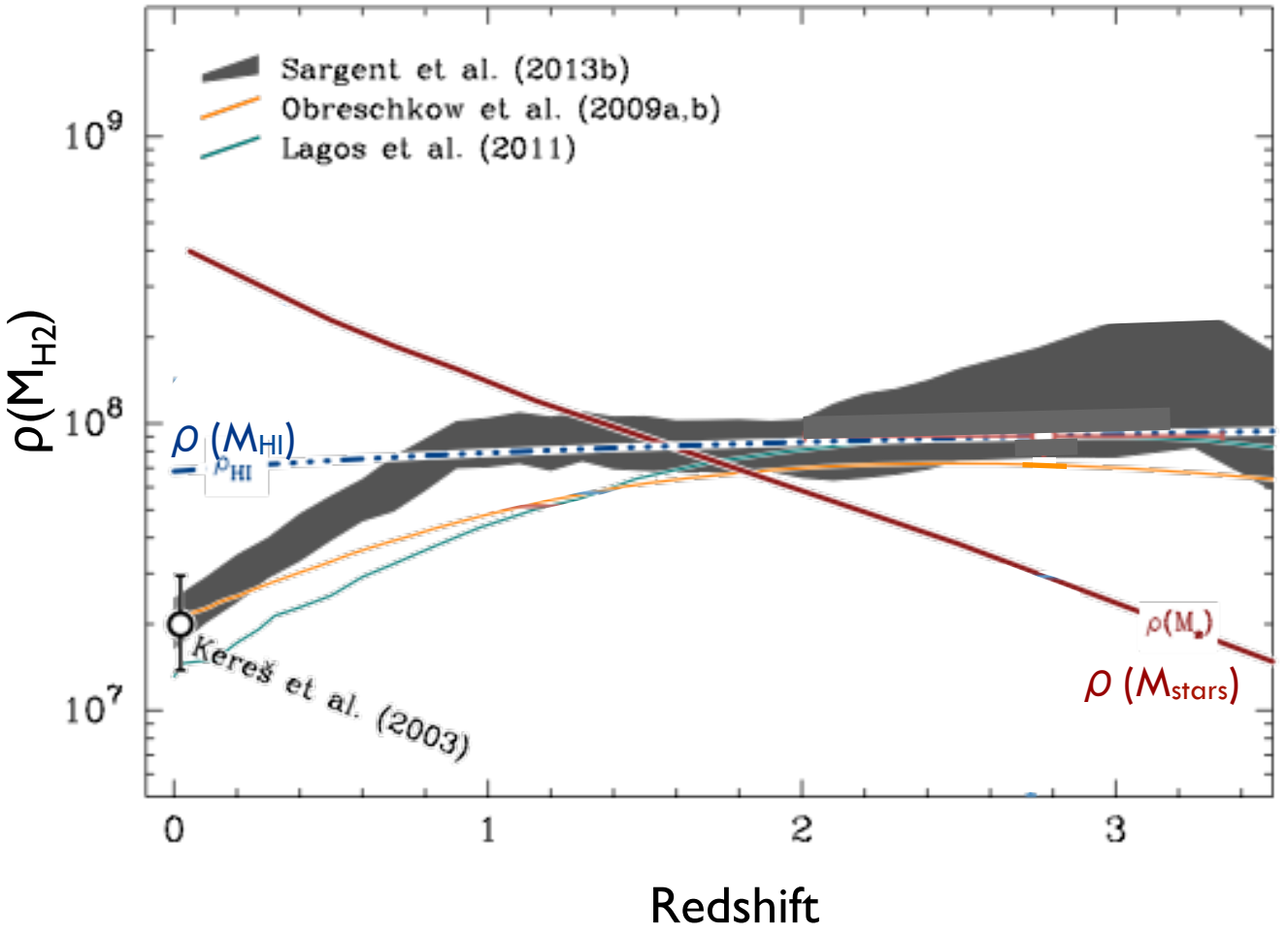


Predictions: H_2 density

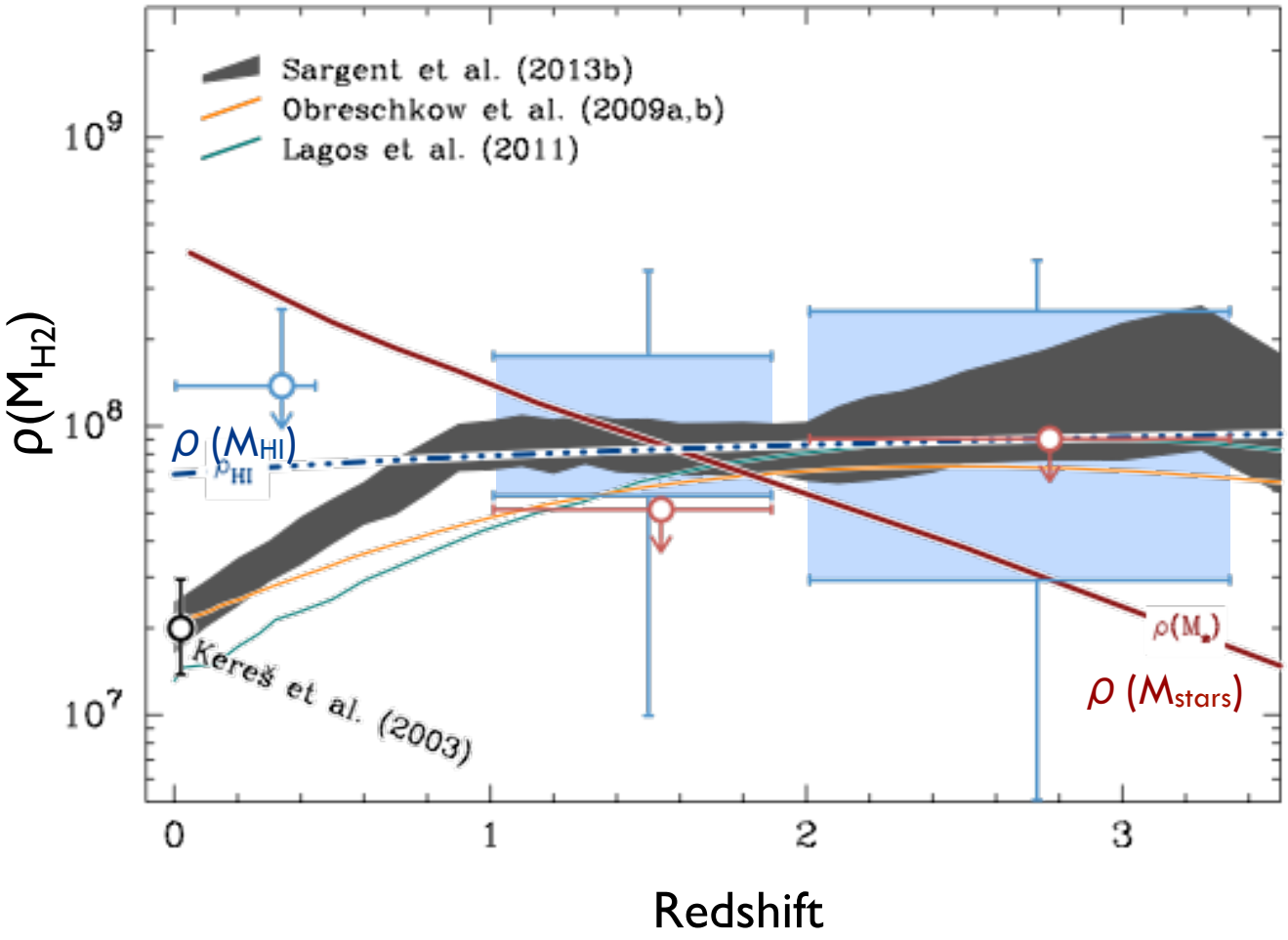
ρ (M_{H2}) predictions + densities of stars and HI



Sargent et al., in prep (based in Sargent et al. 2011, 2012)

Constraints: H_2 density

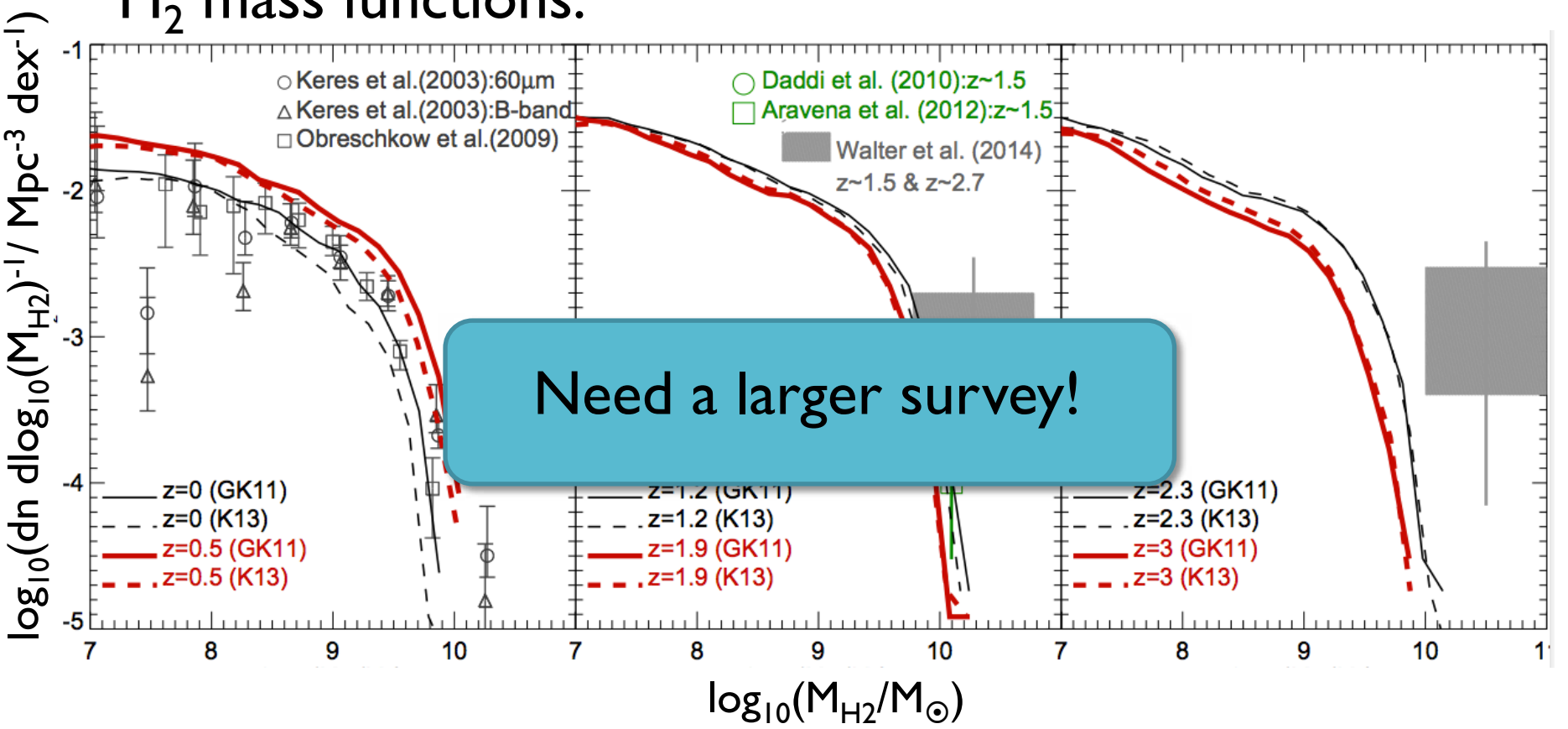
limits from blind detections in HDF



Walter et al. (2014)

Comparison with EAGLE hydro sims

H_2 mass functions:



Need a larger survey!

Lagos et al. (2015)

A large VLA molecular & continuum deep field

- Large VLA program (PI: D. Riechers)
  - Goal: To construct the cold gas history of the universe
- Observing frequency: 34 GHz (9mm; Ka band)
  - CO(1-0) at z~2 (epoch of galaxy assembly)
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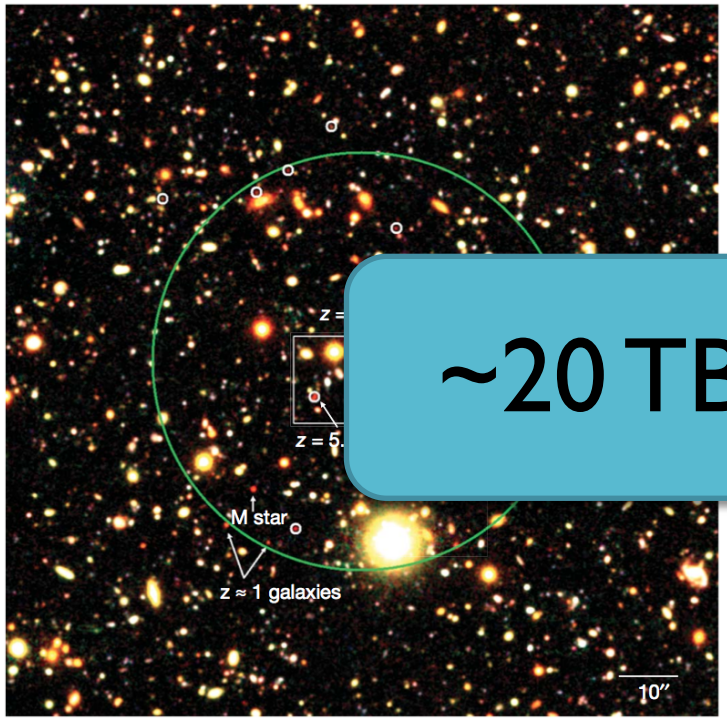
A large VLA molecular & continuum deep field

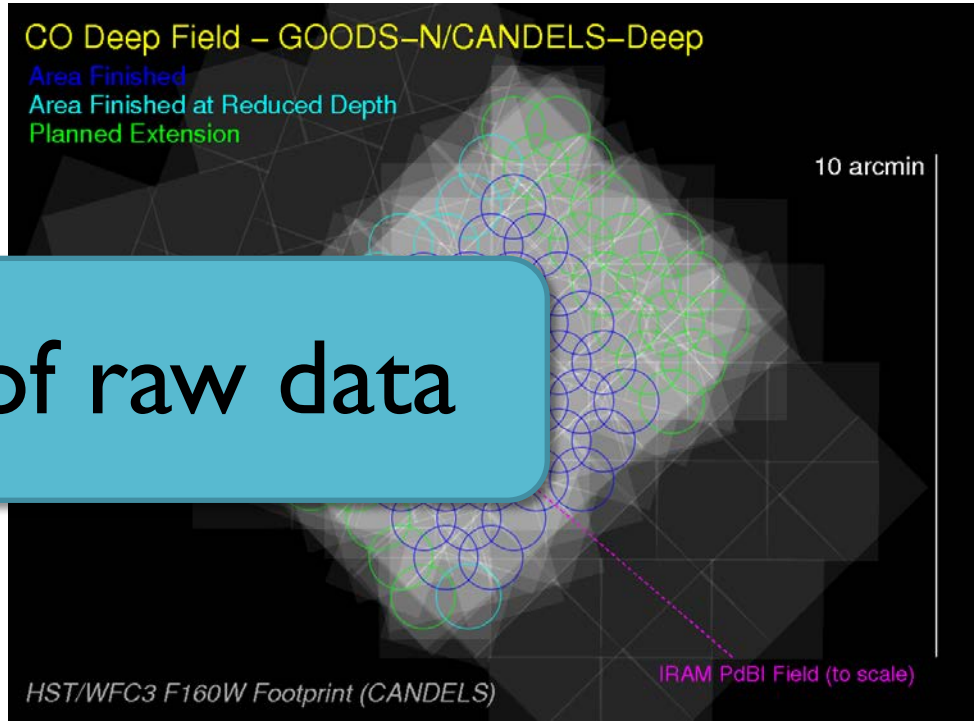
COSMOS: 6.5 arcmin^2 field

7-pointing mosaic



GOODS-N/CANDELS: ~50 arcmin^2 field

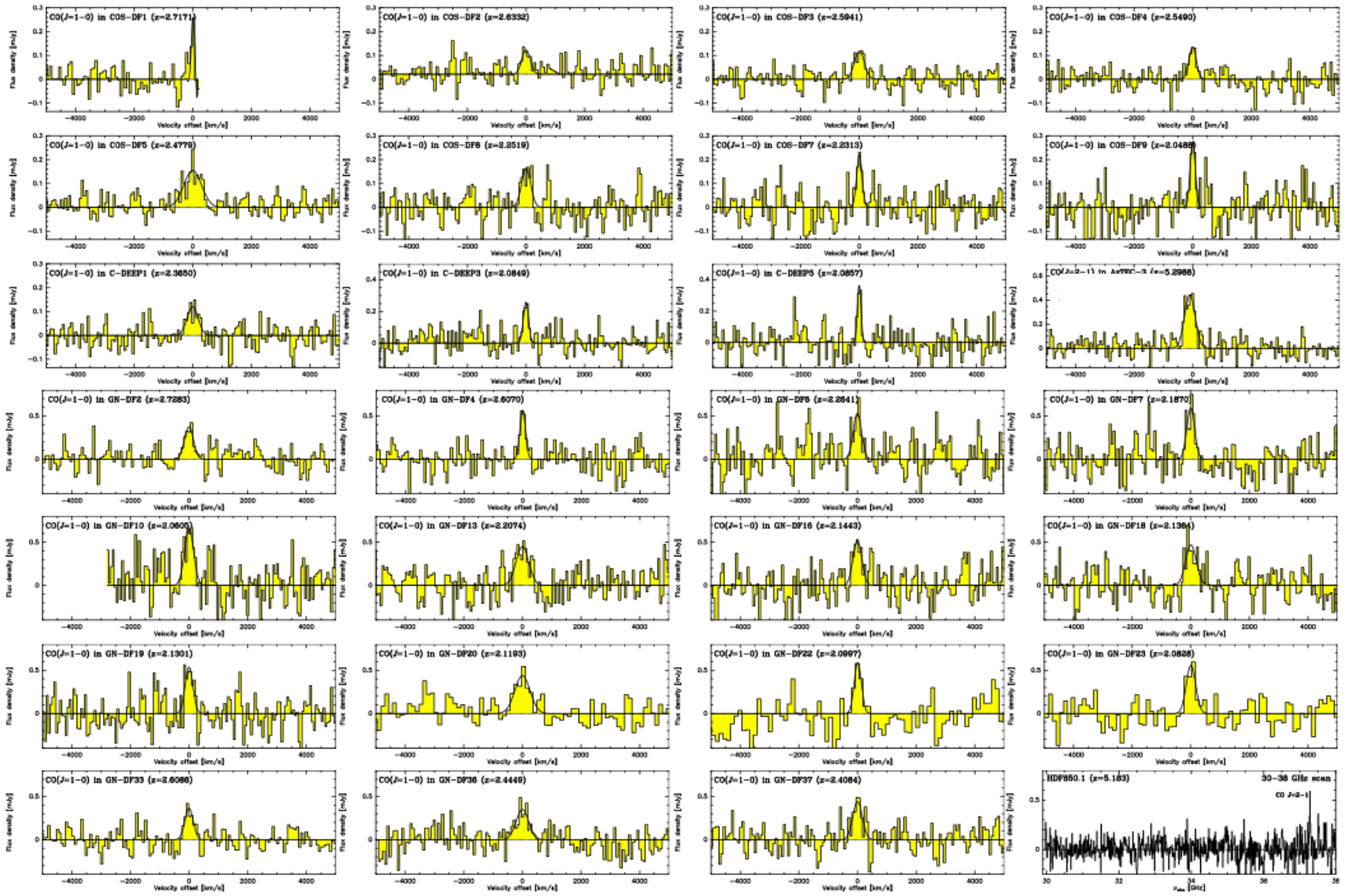
57-pointing mosaic



~20 TB of raw data

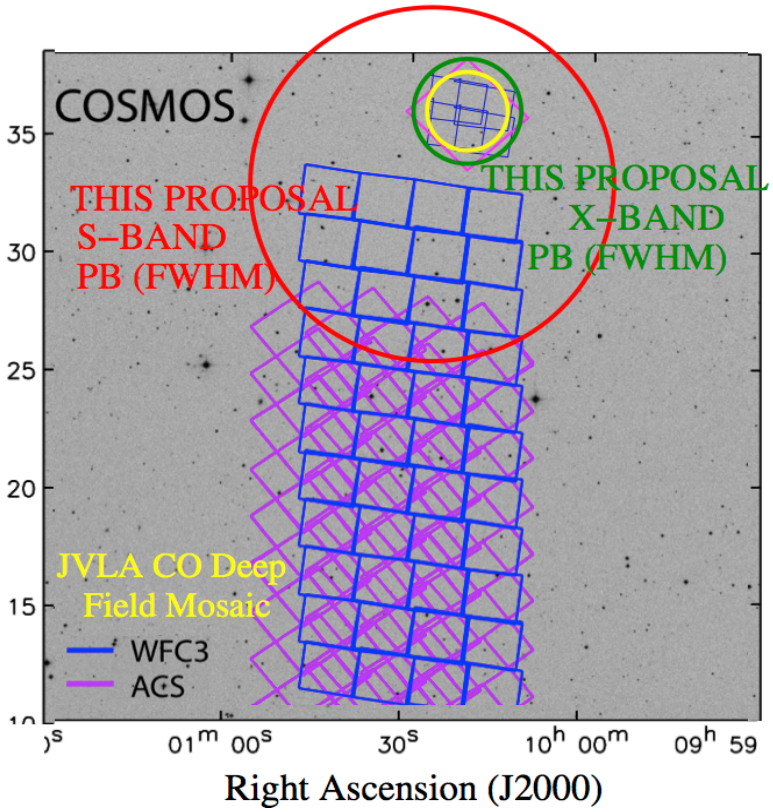
Total area: Currently ~56 arcmin^2

Blind emission line search



An Ultra-deep VLA COSMOS survey (PI: Hodge)

- 190 hours, 3 GHz (0.5 μ Jy/bm) & 10 GHz (0.4 μ Jy/bm) at 2”
- Science Goals:
  - Extend measurements of dust-unbiased SFHU to z~3 MS
  - Constrain dust attenuation
  - Study free-free emission at z>2
  - Study gas-(unobscured) SF connection in galaxies from our blind CO survey



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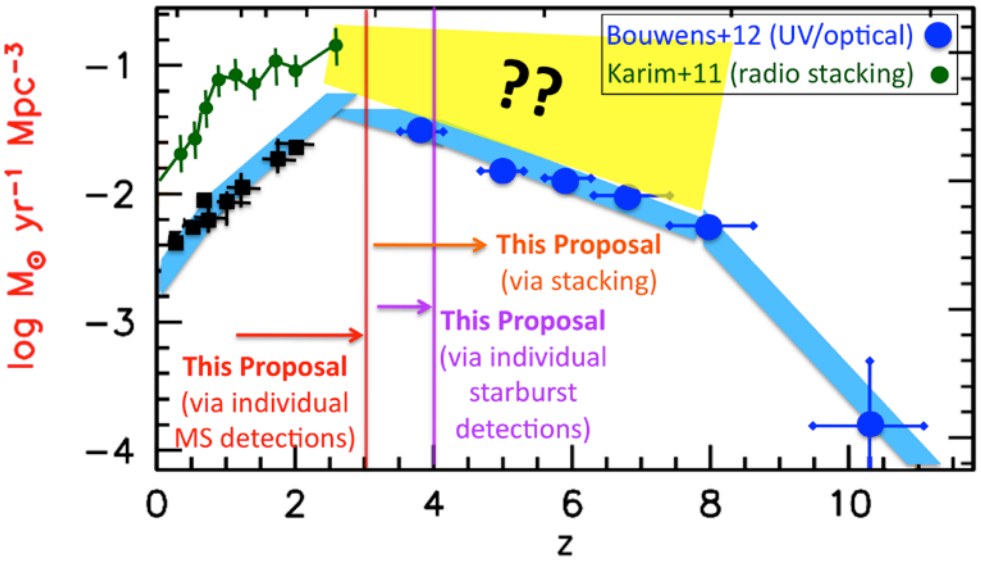

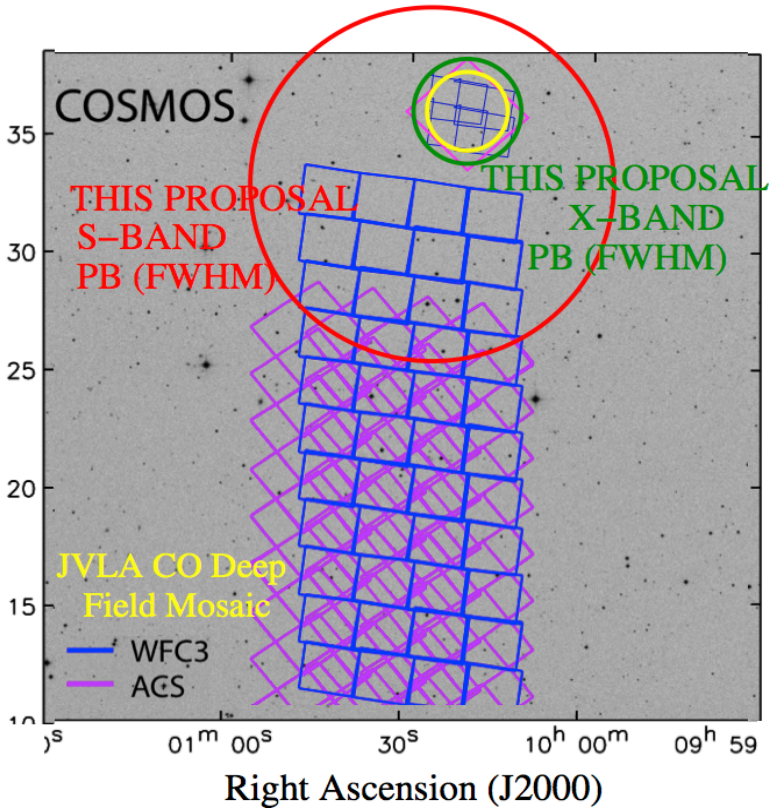

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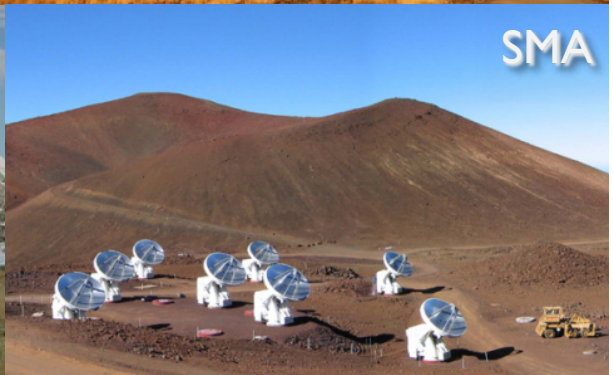

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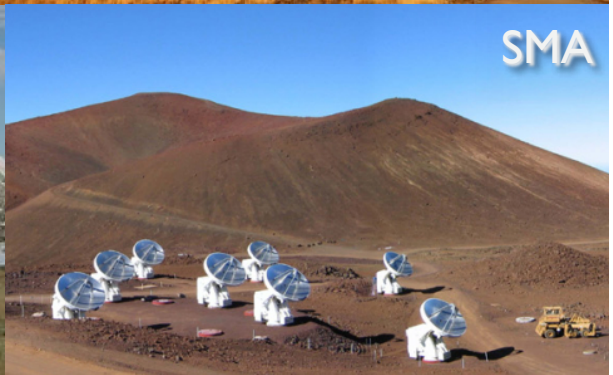
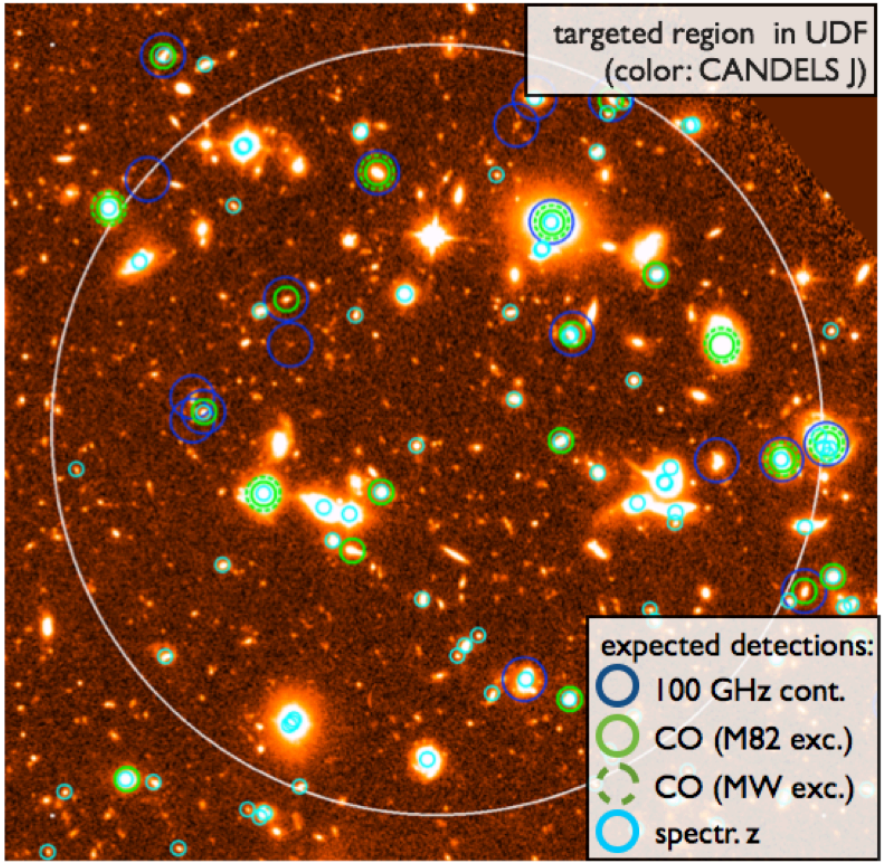


The Future: Molecular deep fields with ALMA

1 arcmin^2 in UDF



Predictions based on da Cunha+13

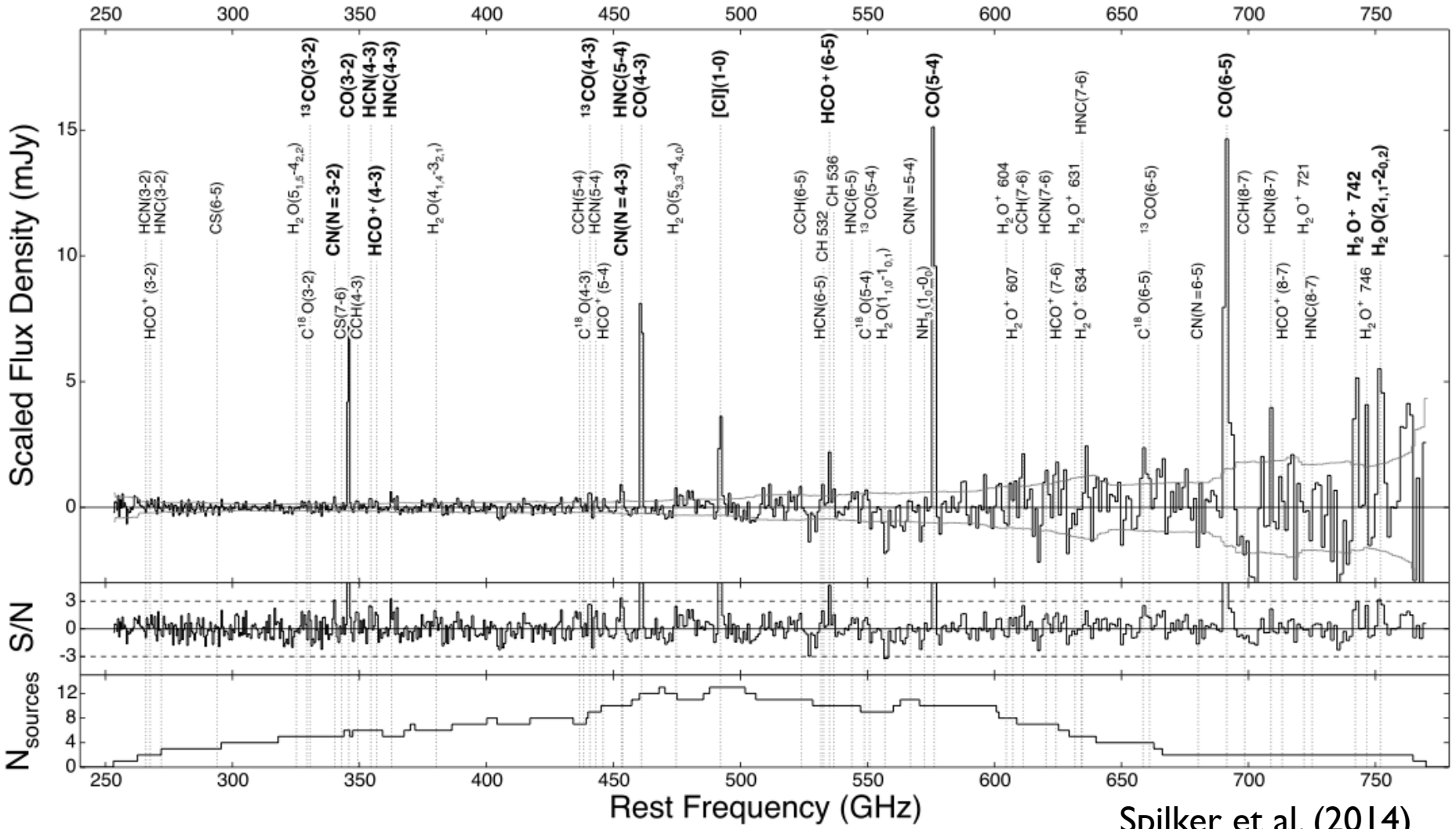
Band 3 PI: Walter

Band 6 PI: Aravena

- Sensitive to CO intensities *an order of magnitude deeper* than currently detected BzK & BM/BX-selected galaxies
- Jointly, these programs will constrain CO LF below expected knee

The Future: Moving beyond CO

Composite spectrum from 22 lensed SMGs from ALMA Cycle 0



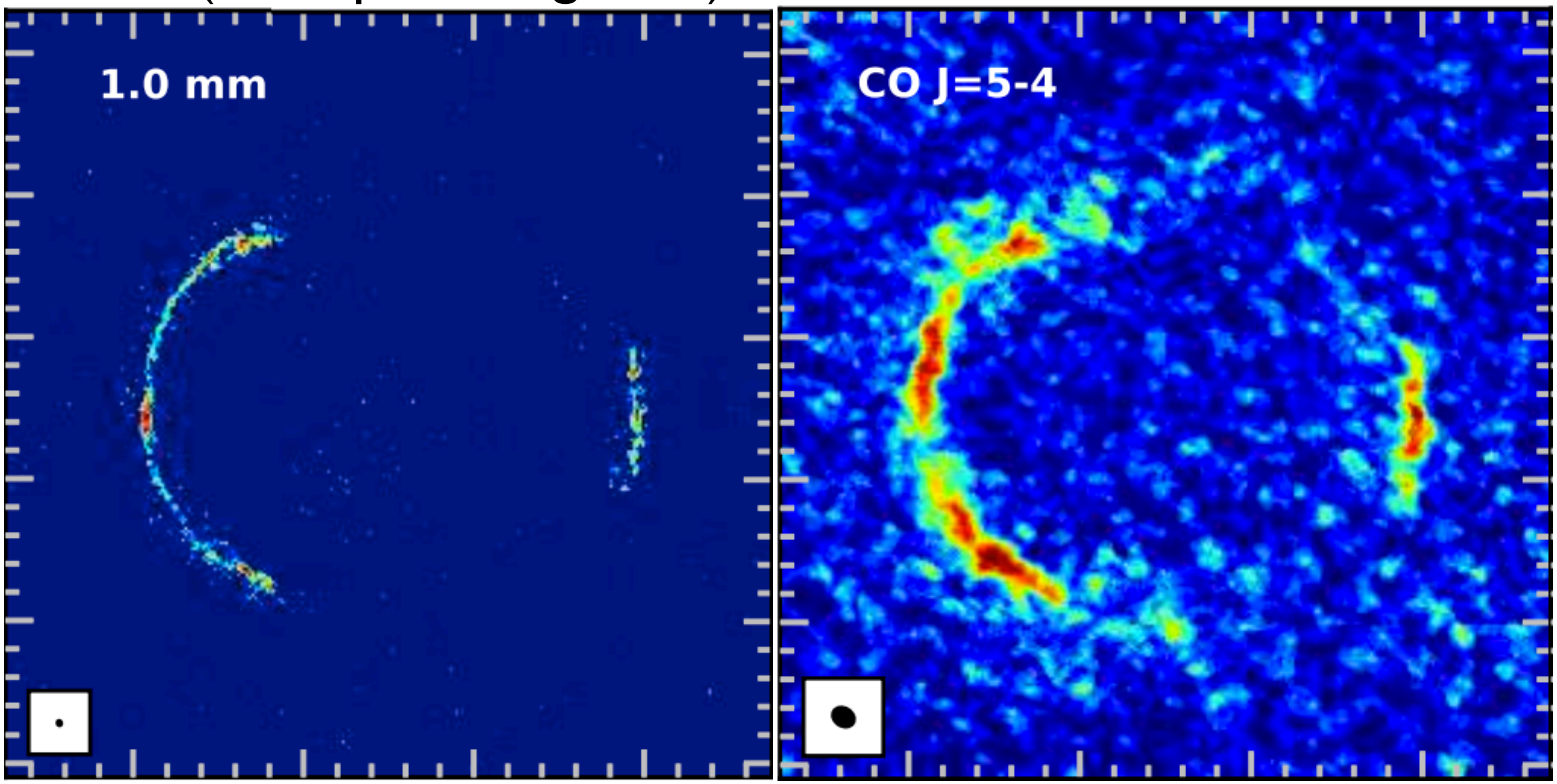
Spilker et al. (2014)

The Future: (Sub-)kpc scales!

Strongly lensed submillimeter galaxy at z~3

0.03" (~200 pc unmagnified)

0.17" (~1 kpc unmagnified)



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

Summary

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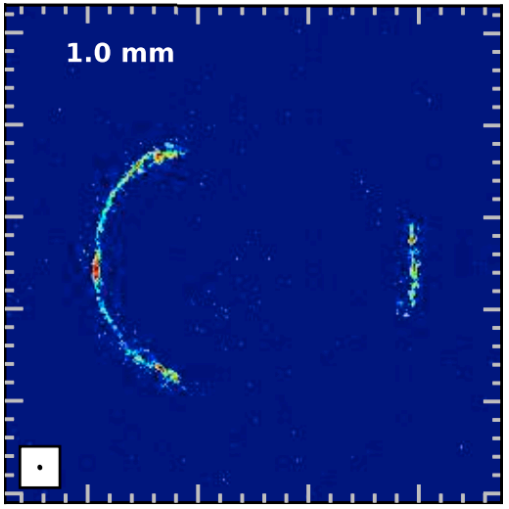
- Future is bright: ALMA molecular deep fields, molecular astrochemistry, and (sub-)kpc scales

The Future: Pushing down to *sub*-kpc scales

- ALMA's most extended configurations will reach scales of *<100 pc !!*

Strongly-lensed SMG
SDP.81



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

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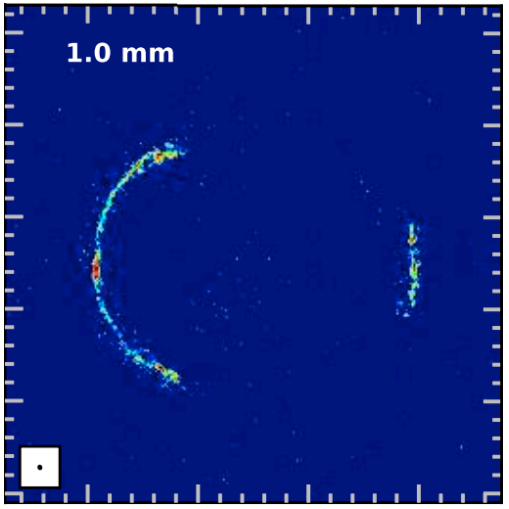


The ALMA Partnership, Vlahakis, Hunter, Hodge et al. (2015)

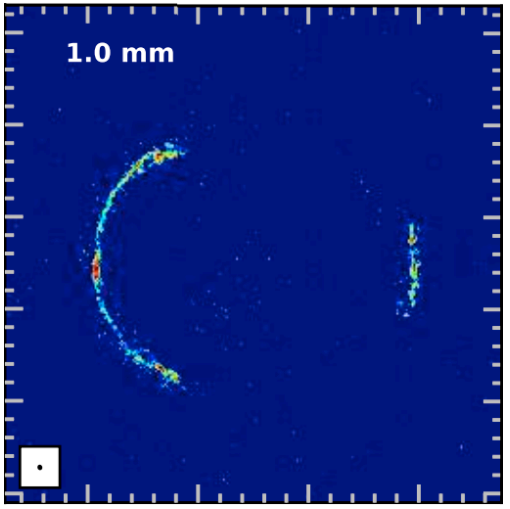
Will help address:

- The nature of the extreme SF
- What SMGs evolve into
- The prevalence/properties of high-z molecular outflows

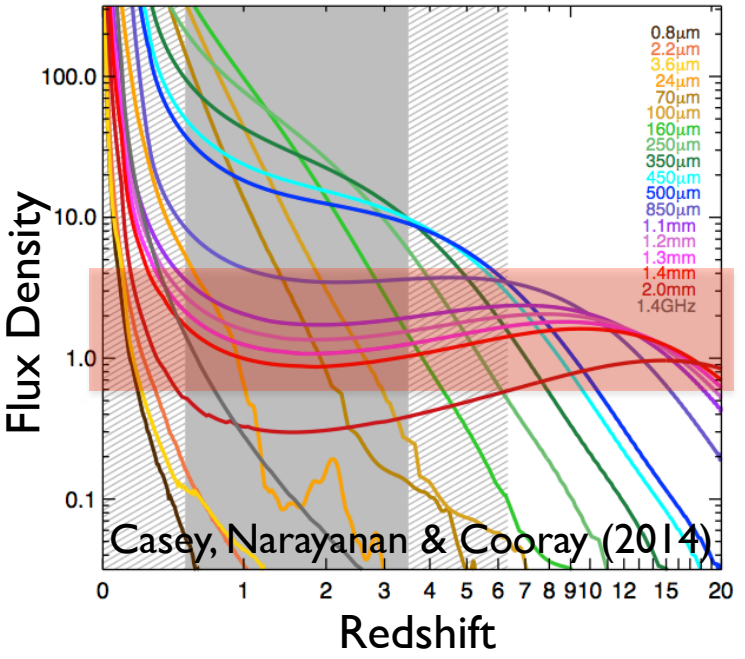
The Future: Pushing down to *sub*-kpc scales

- ALMA's most extended configurations will reach scales of *<100 pc !!*

Strongly-lensed SMG SDP.81



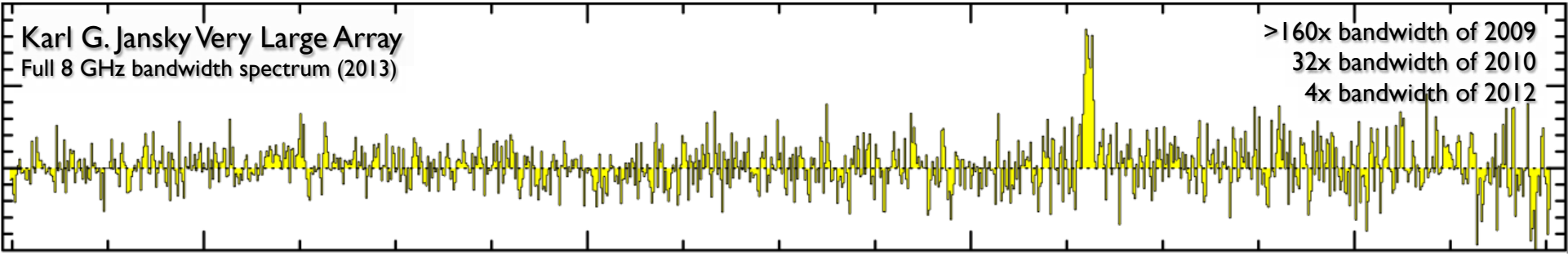
Negative k-correction



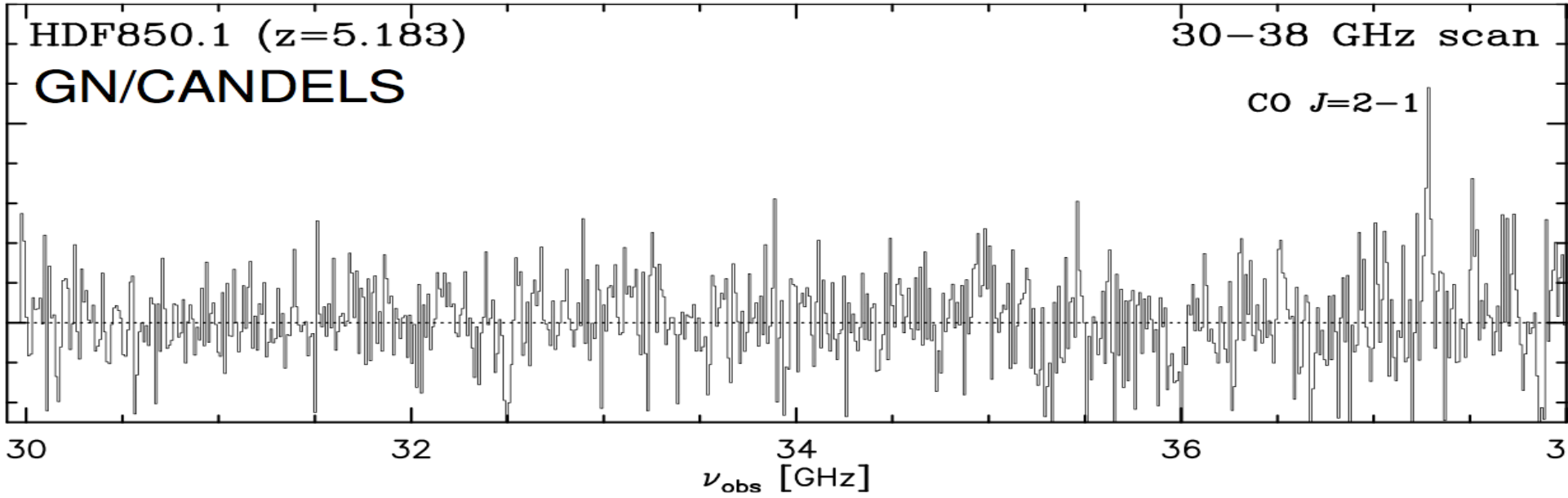
- Will resolve individual star-forming clouds in unlensed galaxies…

…out to the highest redshifts!

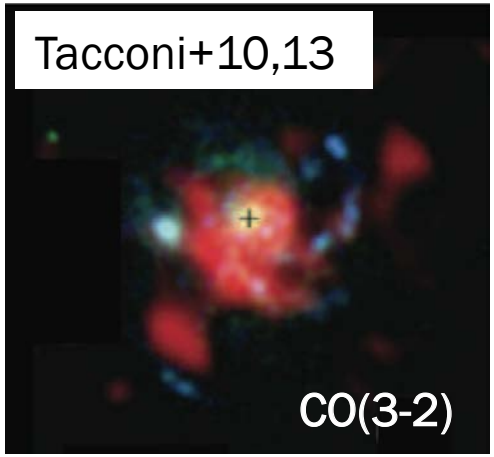
Molecular emission line sources

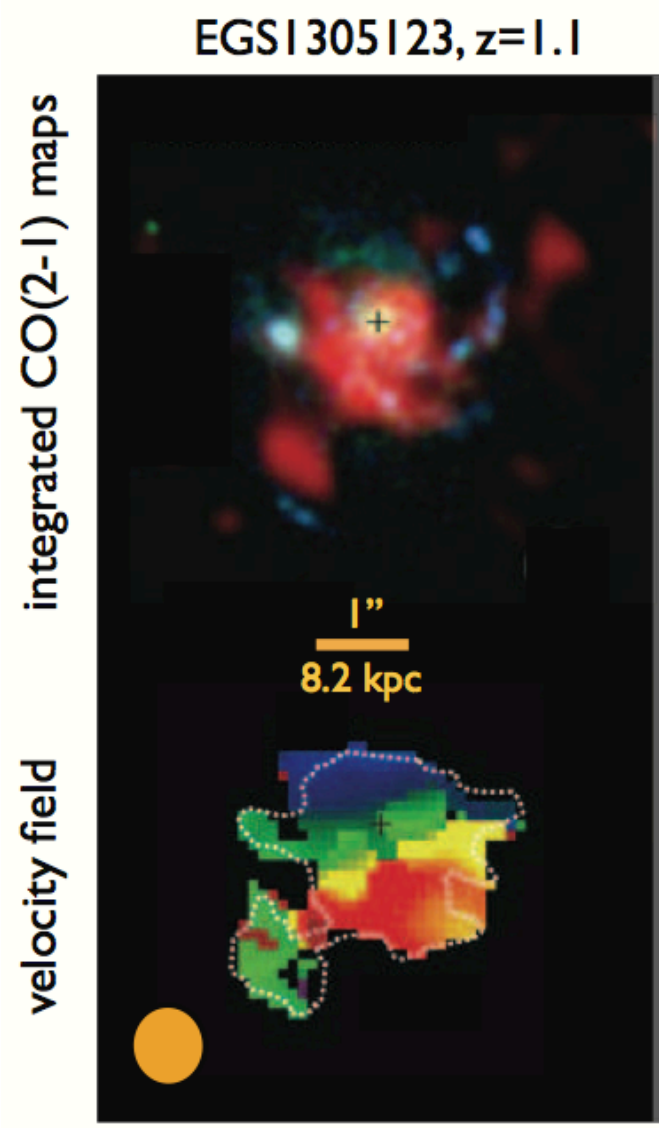


CO J=2-1 in z=5.3 dusty galaxy – the most distant known 2010-2013, our "line calibrator source"

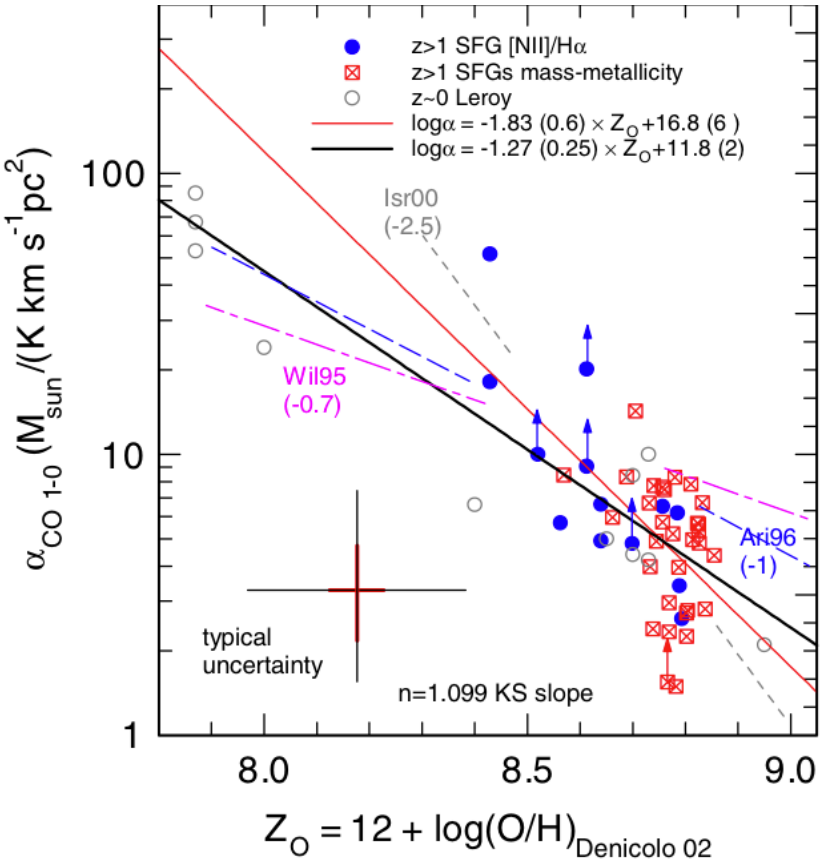


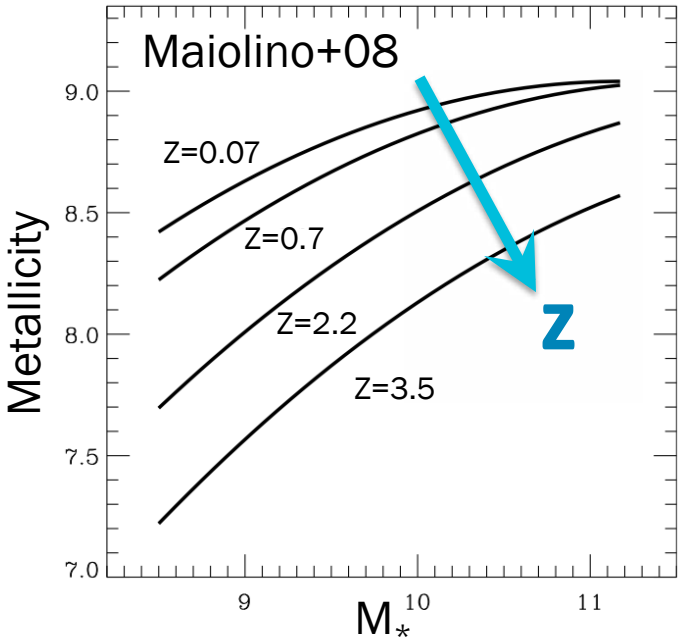
Detailed views





Conversion factor changes with z





Genzel+12
(See also Tan+submitted)

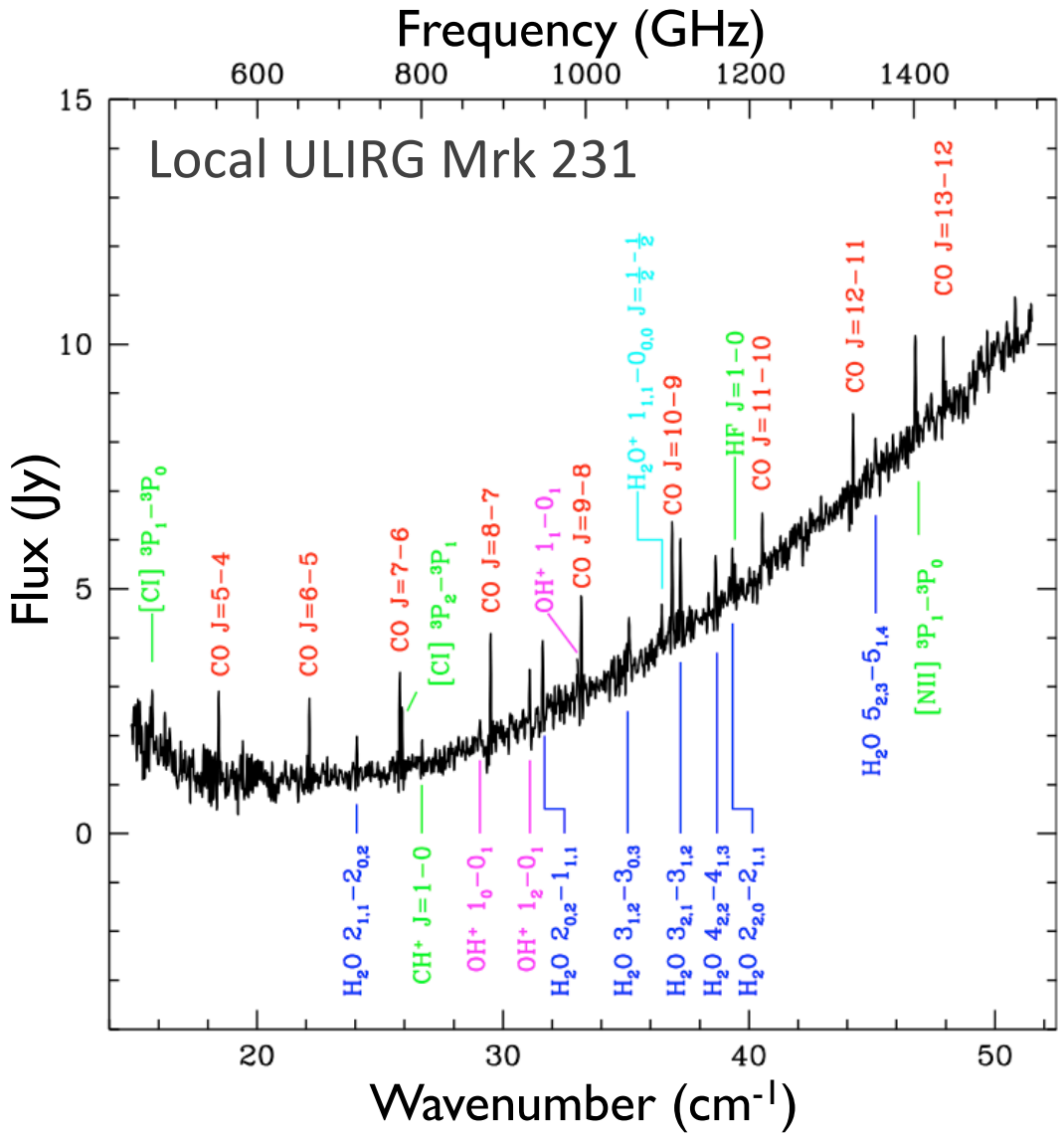
At z~3.5, a 10^{11} $M_\odot$ galaxy has $Z = 0.5\ Z_\odot$
➔ α_{CO} = 2.5–4 times larger

A large VLA molecular & continuum deep field

- Large VLA program (PI: D. Riechers)
  - Goal: To construct the cold gas history of the universe
- Observing frequency: 34 GHz (9mm; Ka band)
  - CO(1-0) at z~2 (epoch of galaxy assembly)
  - CO(2-1) at z~5.5
- Configurations: D, DnC, & C
- Resolution: ~2”
- Observing time: ~500h
  - 391h in D-config
  - 115h in C-config

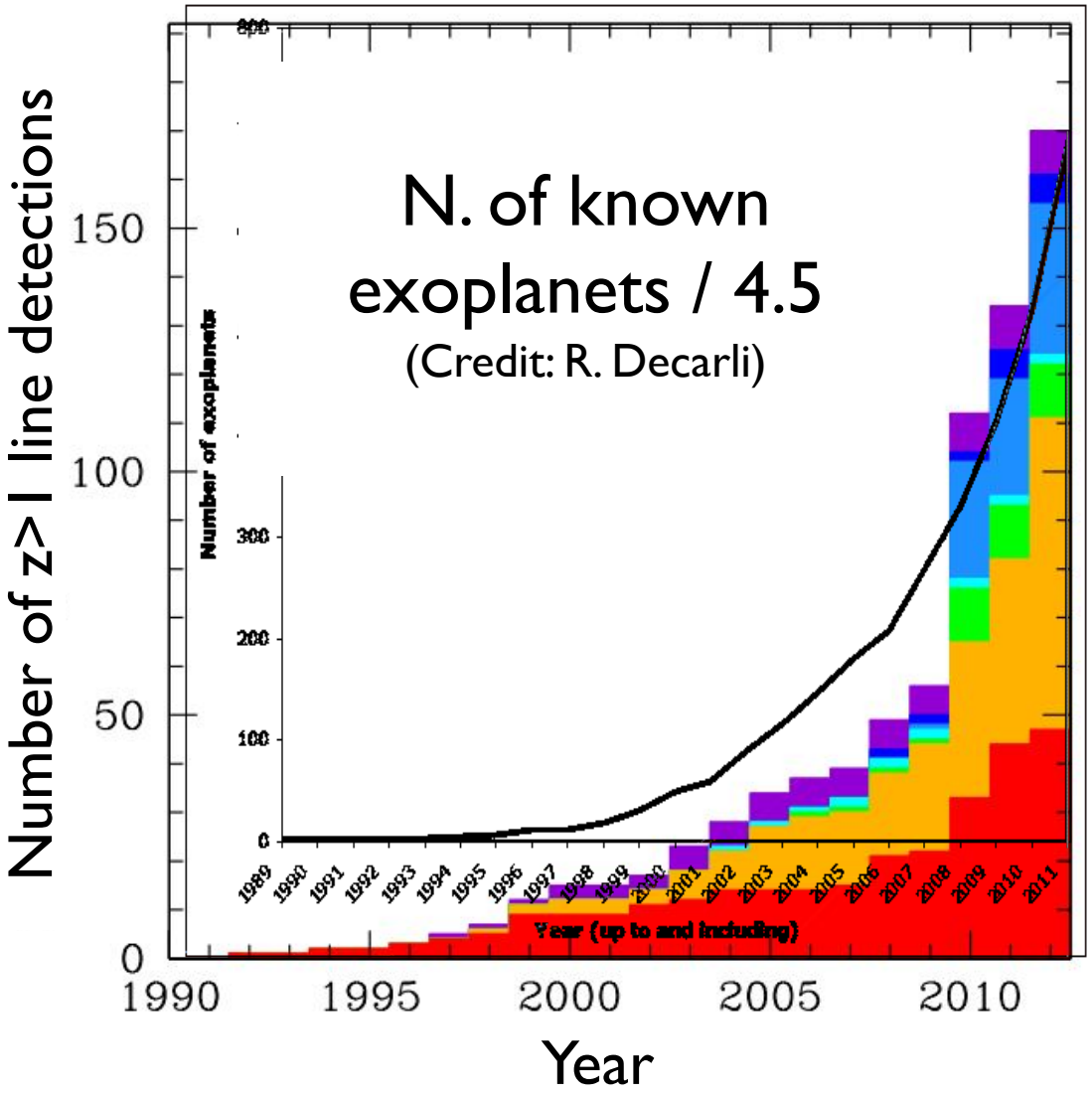
- Bandwidth: 8 GHz (frequency-dithered, contiguous coverage)
- Possible now for first time! (>160X BW increase since 2009)

The Future: Moving Beyond CO



van der Werf et al. (2010)

High-z molecular gas detections



Carilli & Walter (2013)