Studies of Galaxies in the Early Universe:

High Redshift Gas, Dust, and Star Formation as seen by ALMA and the Jansky VLA

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Atacama Large Millimeter/submillimeter Array

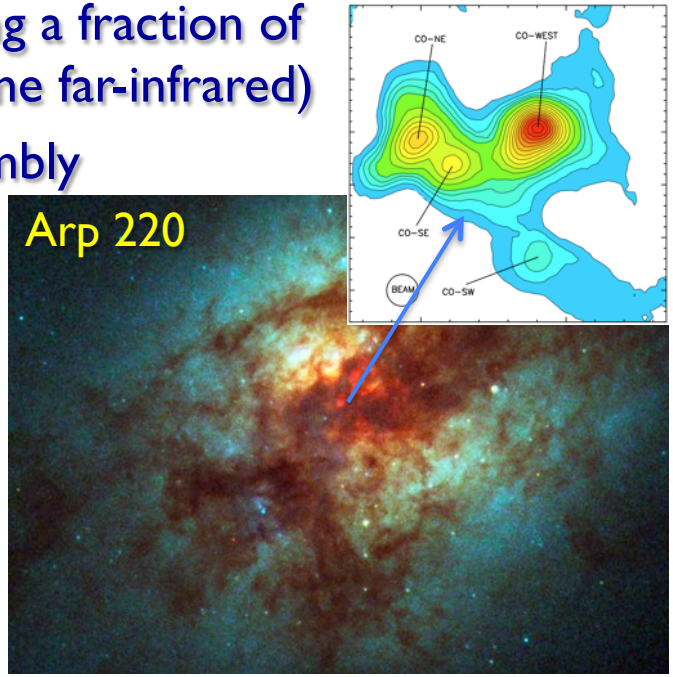
Karl G. Jansky Very Large Array

Robert C. Byrd Green Bank Telescope

Very Long Baseline Array

A New Era for Studies in Galaxy Evolution

- UV/optical studies of *stars* and *star formation* in galaxies reach back to a few hundred million years after the Big Bang
- sites of star formation enshrouded by *dust*, absorbing a fraction of the stellar light (which is re-radiated in the rest-frame far-infrared)
- Studies are missing *cold gas*, the fuel for galaxy assembly



ALMA and the Jansky VLA are the ideal tools to probe this "hidden" component, revealing:

⇒ how and when the first stars and galaxies form

⇒ how galaxies assemble and evolve with cosmic time

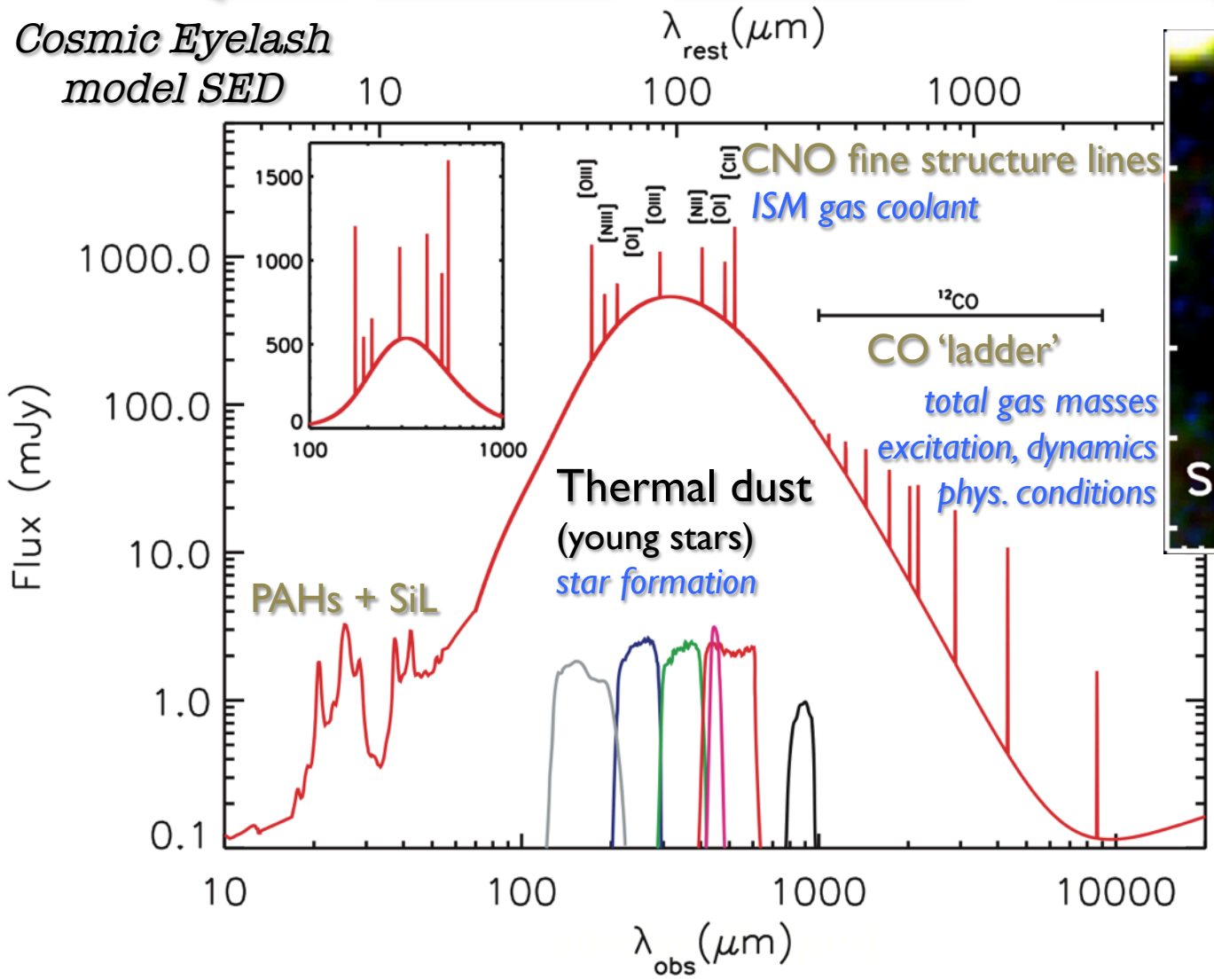
⇒ the co-evolution of massive black holes and their host galaxies

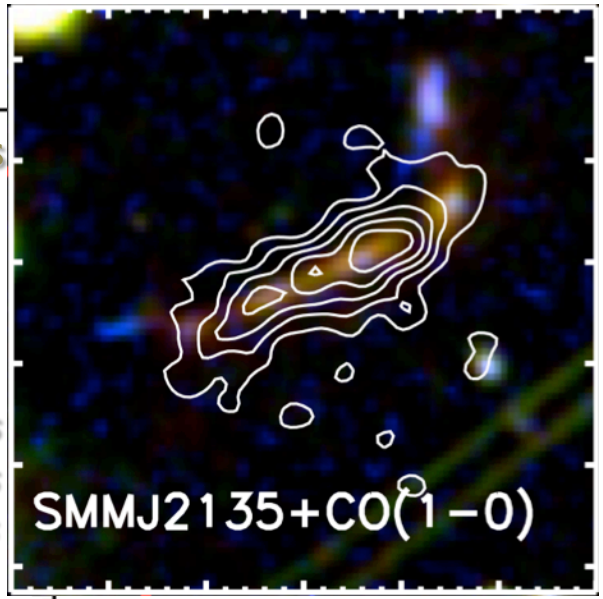
⇒ the role of environment for the formation and evolution of galaxies

Radio Astronomy: Unveiling the Cold, Obscured Universe

cm/mm: rich in line + continuum diagnostics

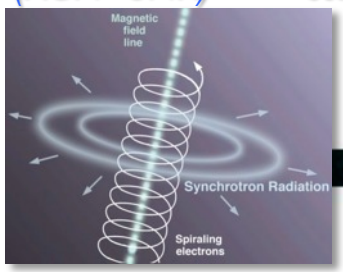
JWST — SPICA — ALMA+CCAT — JVLA



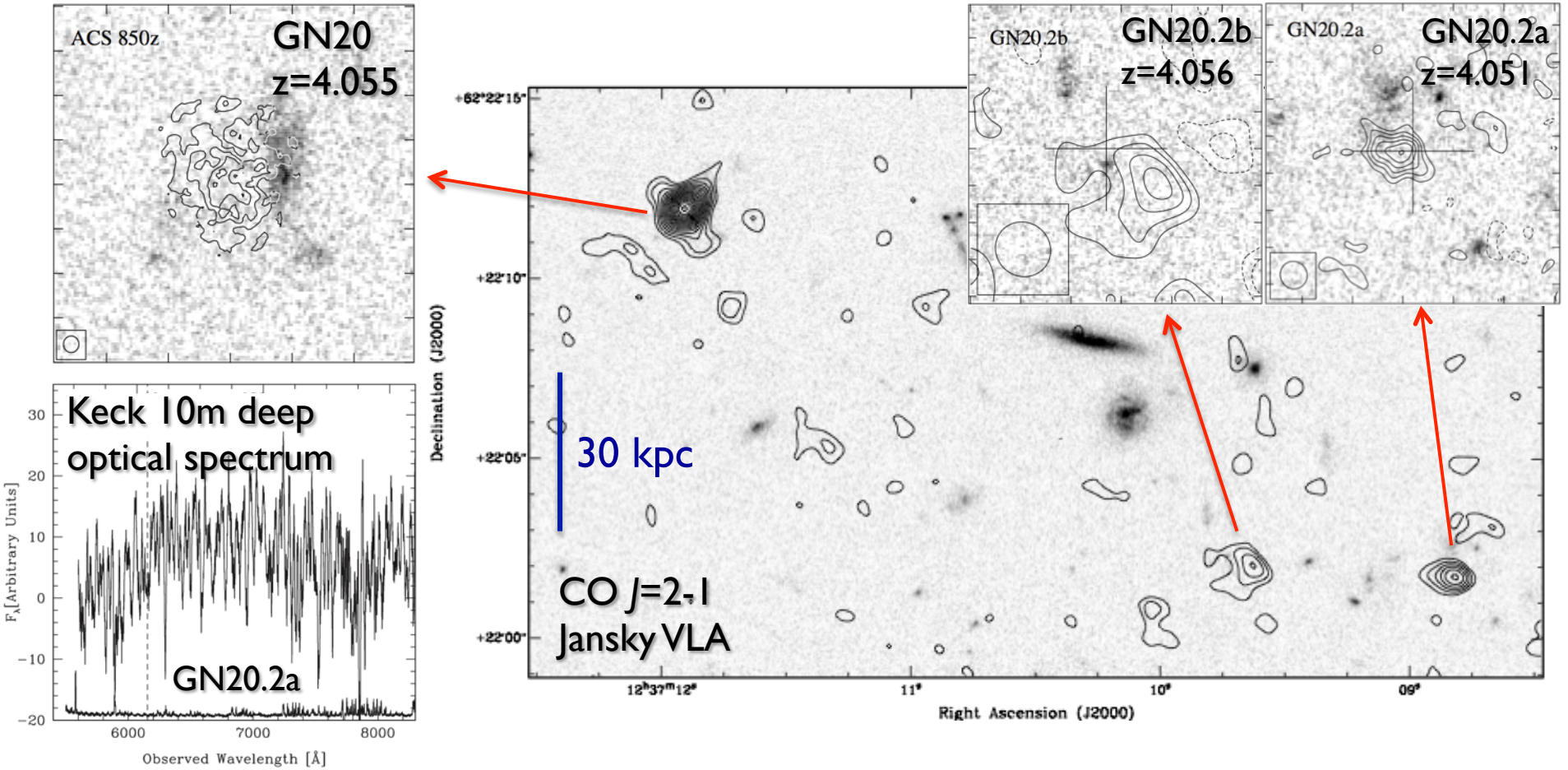


Smail et al. 2011
Swinbank et al. 2011

Synchrotron + Free-Free
(AGN+SNR) star formation



Molecular Gas in a Group of Submillimeter Galaxies at z=4.05

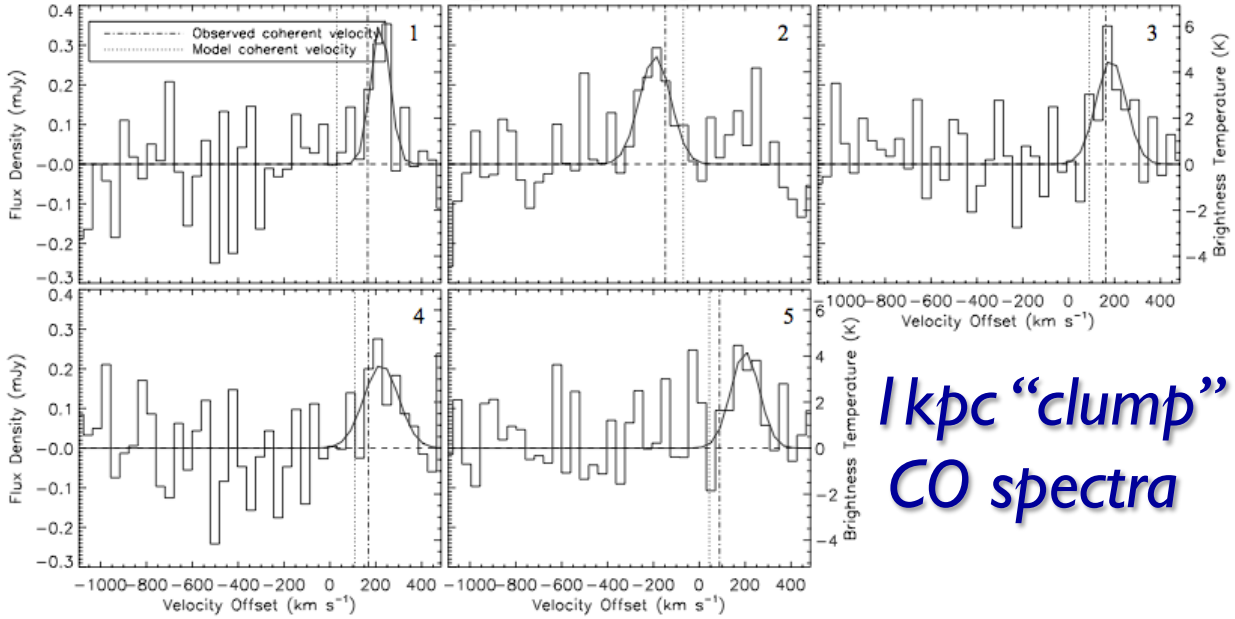


- Jansky VLA Key Program (0.15"/1.0kpc resolution @ 7mm)

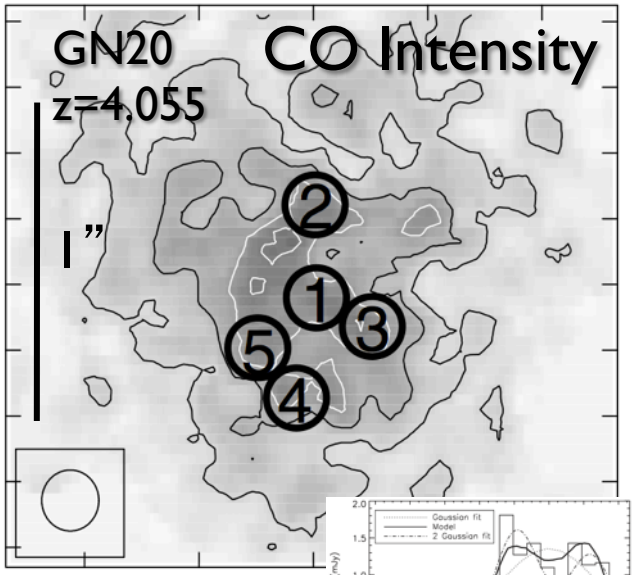
⇒ Clustered, massive galaxy formation at t_{univ} ~ 1.6Gyr

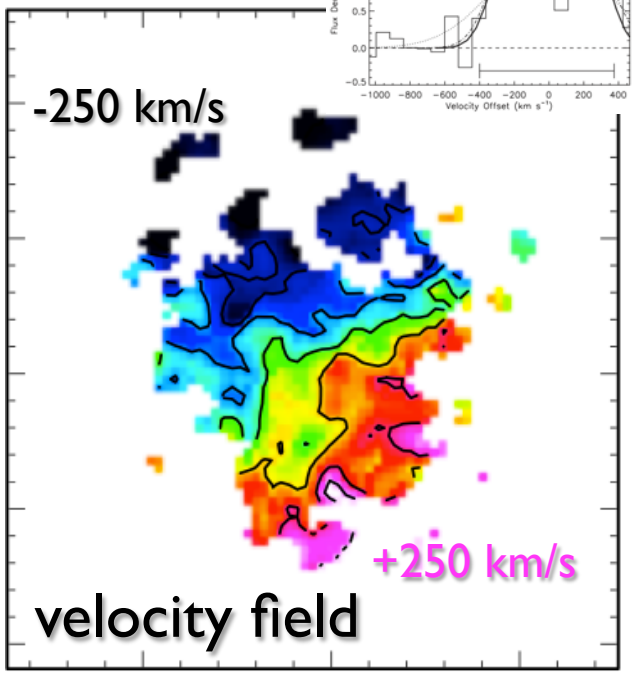
Carilli et al. (2010, 2011); Hodge et al. (2012, 2013)

GN20: A Large Gas Disk with Self-Gravitating Clumps



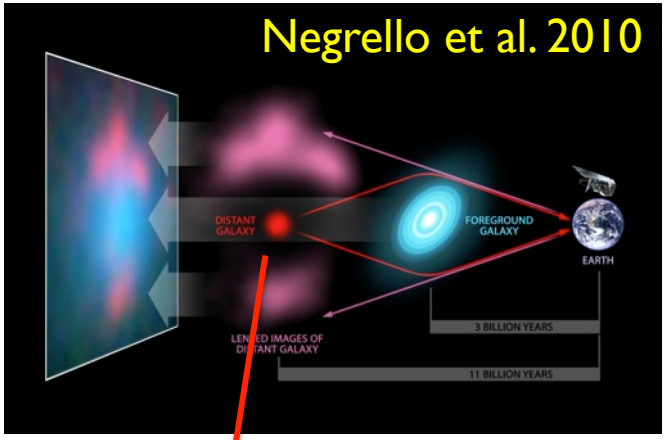
1kpc "clump" CO spectra





- massive starburst: SFR ~ 3000 M_{sun}/yr
- CO: large, rotating gas disk (~14 kpc across)
- M_{dyn} = 5.4 10^{11} M_{sun} (~25% molecular gas)
- kpc-size clumps: M_{dyn} ~ M_{gas} ~ 10^9 M_{sun}

"Z-Machines": "Blind" CO Detections

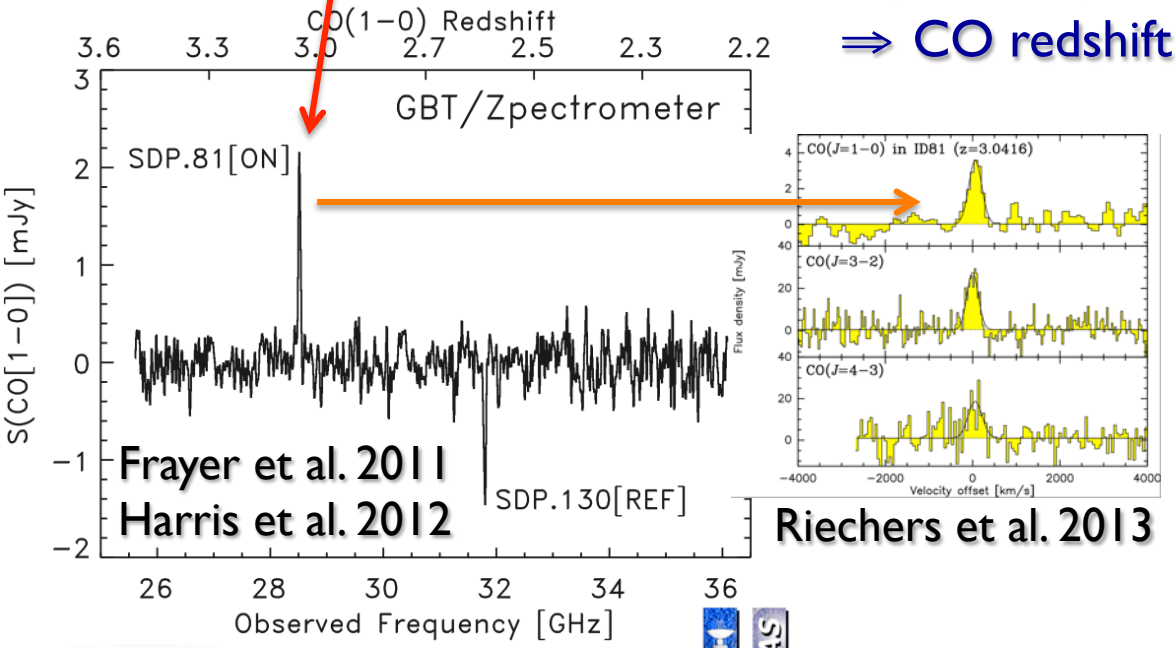


Zpectrometer PI instrument on GBT:
- Covers *1cm* band (12.1 GHz bandwidth)

⇒ "Blind" CO(J=1-0) detections at z=2.1-3.5

Successful:
- 12 lensed SMGs from Herschel detected
- CARMA *3mm* high-J CO confirms all

⇒ CO redshift machines work!



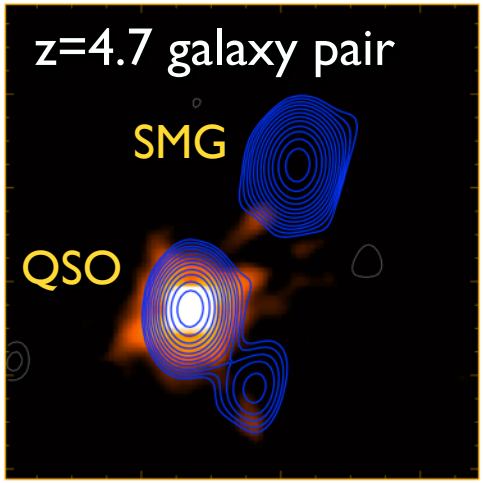
JVLA+ALMA: powerful duet (cm+mm) 8 GHz bandwidth

⇒ Will become "*z-machines*"

⇒ Eliminates redshift bias in future deep surveys!

HERSCHEL ATLAS

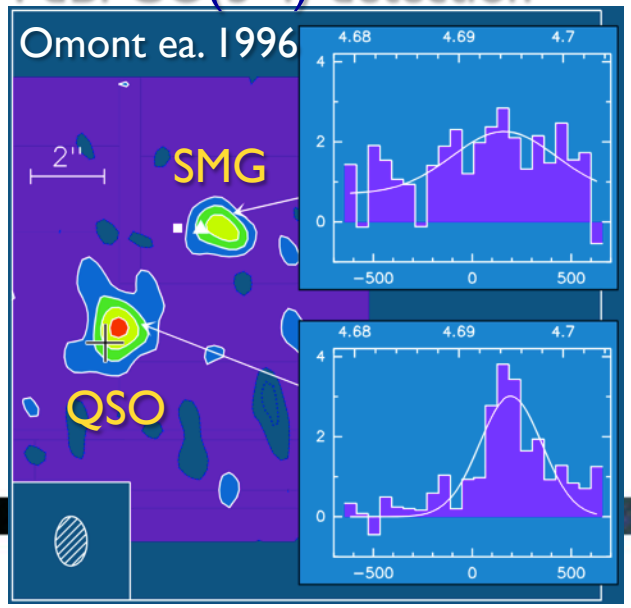
ALMA: 1st High-z Image

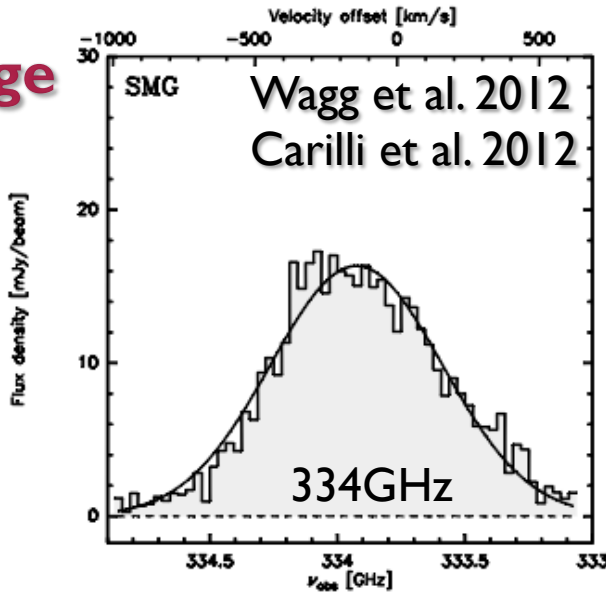


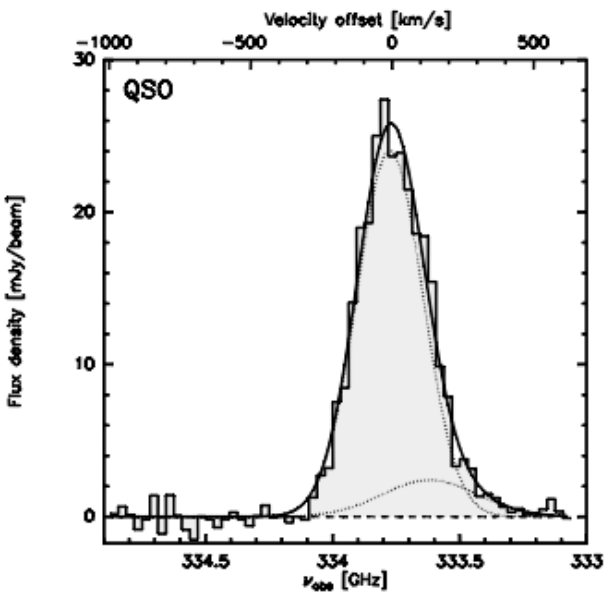
ALMA 330 GHz continuum

⇒ *Both galaxies L_{FIR} >10^{13} L_{sun}*

PdBI CO(5-4) detection



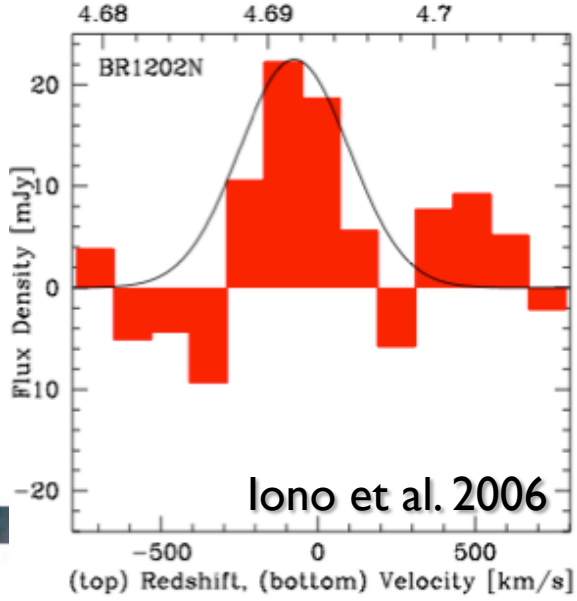


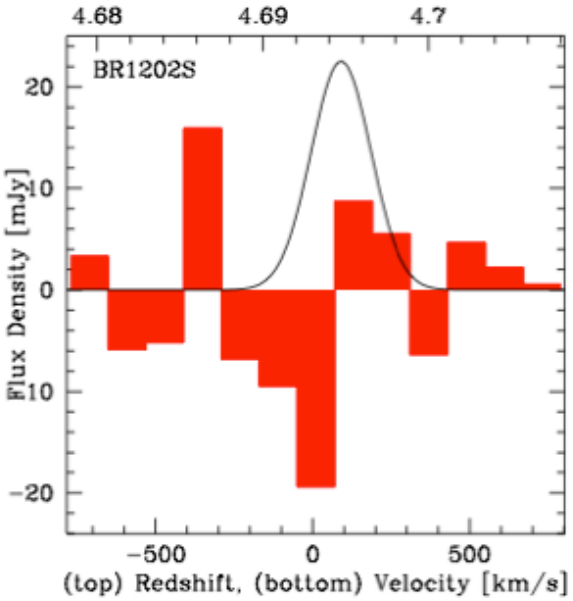


ALMA 20min, 16 ants (~2min full ALMA)

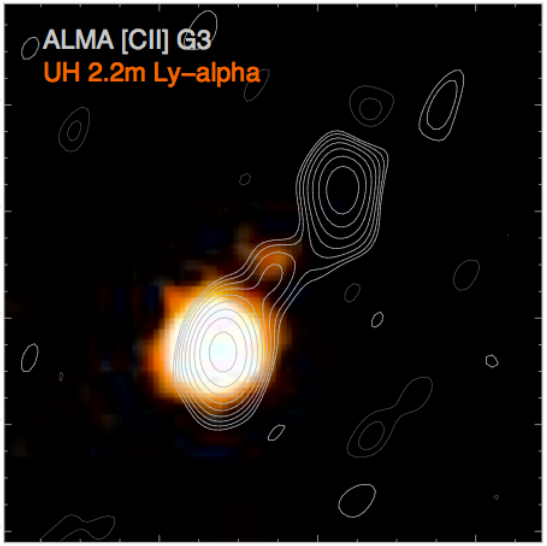
SMA 20hrs

[CII] 158μm ISM cooling line

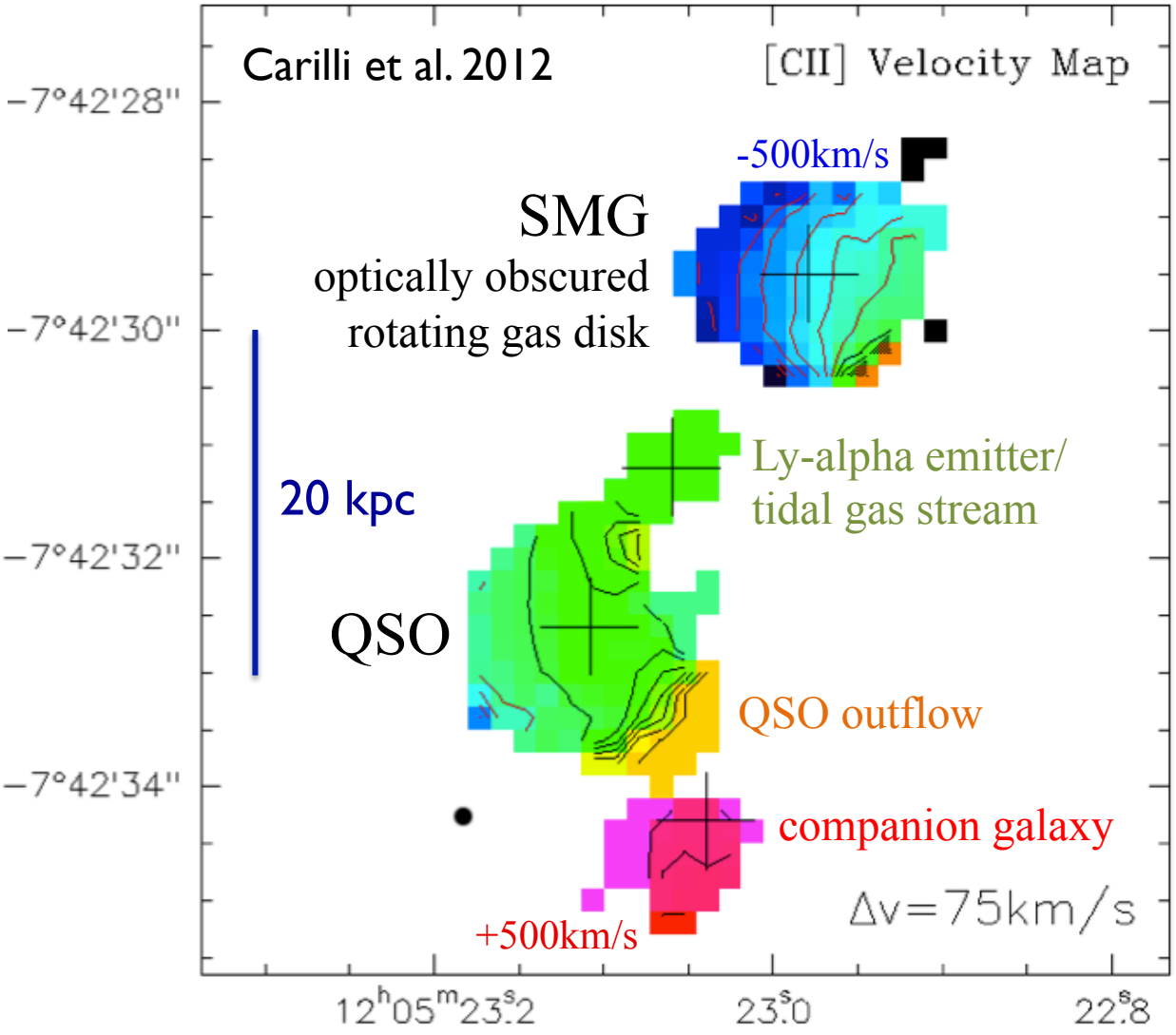




ALMA [CII] Mapping of z=4.7 Quasar-SMG pair BR1202-0725

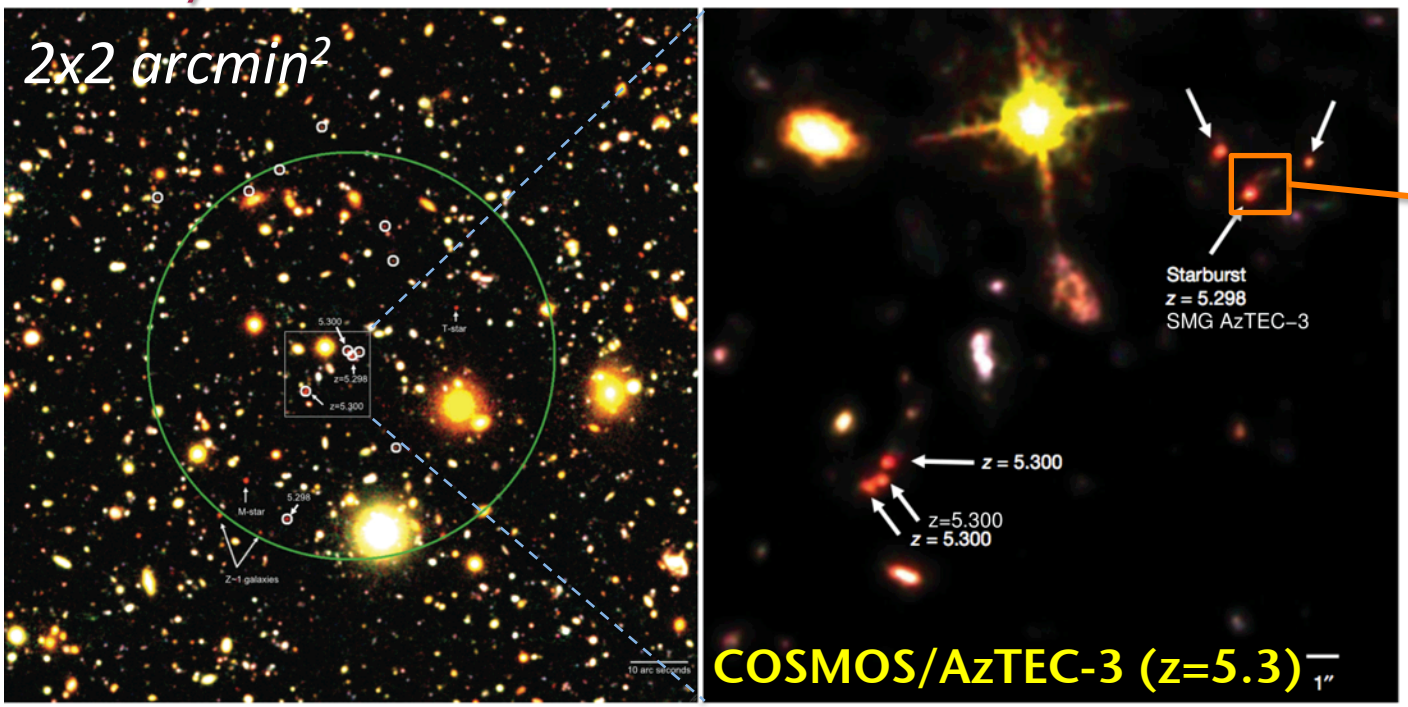


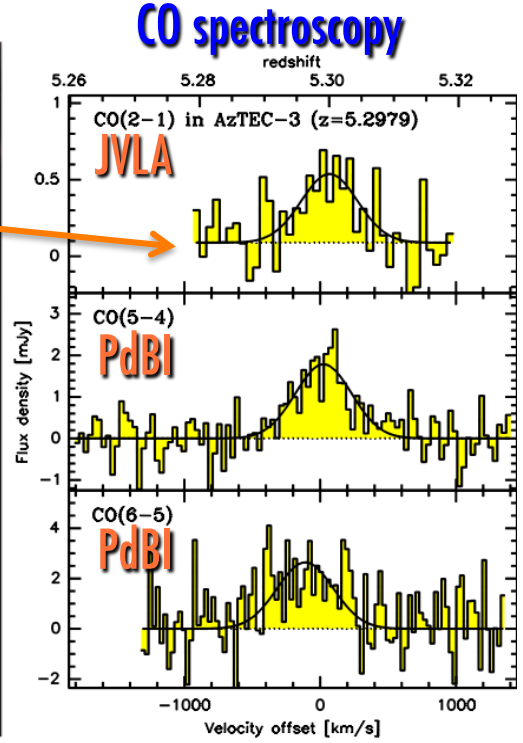
Lyman-alpha image



Formation of Most Distant Galaxy Protoclusters

Galaxy Evolution vs. Environment





- Most Distant *Massive Starburst Galaxy (SMG)* known (2010-2013):
  M_{H2} = 5.3 x 10^{10} M_{sun} SFR >1800 M_{sun}/yr
- Most Distant Galaxy *Proto-Cluster*:
  11 Lyman-break galaxy companions within r~2 Mpc, structure extends to >14 Mpc

Capak et al. 2011, Riechers et al. 2010

Summary: Exciting Times Ahead

- Even with a fraction of its full science capabilities, ALMA knows to impress:

- Detect the dust and interstellar gas in starburst galaxies out to z>6
- Detect and dynamically resolve gas in "typical" z>5 galaxies
- "Blind" spectroscopic detection of previously unknown faint, dusty galaxies

⇒ *already probes uncharted territory in galaxy evolution studies at high redshift*

- JVLA key in the age of ALMA: low-*J* CO & dense gas out to very high z

- Secure measurement of total gas masses
- Investigate dense, actively star-forming gas and chemistry "for free"
- With full 8 GHz bandwidth, will become "redshift machine"

⇒ Study formation of massive galaxies and clusters and their cold and dense gas reservoirs and gas fractions

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