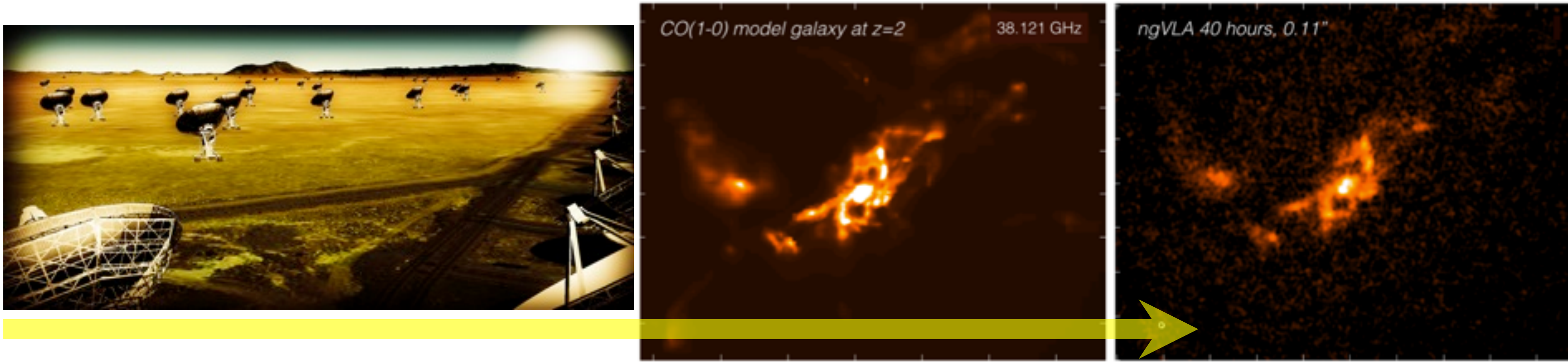


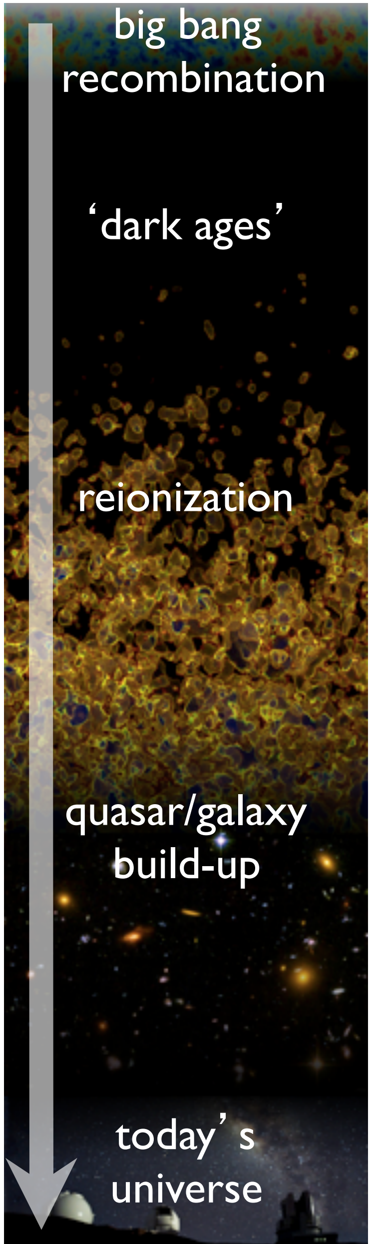
ngVLA: Galaxy Assembly through Cosmic Time

Dominik A. Riechers (Cornell)

On behalf of the ngVLA high-z working group:

Caitlin Casey, Jacqueline Hodge, Mark Lacy, Katherine Alatalo, Amy Barger, Sanjay Bhatnagar, Chris Carilli, Christopher Hales, Rob Ivison, Amy Kimball, Kotaro Kohno, Carol Lonsdale, Eric Murphy, Desika Narayanan, Chelsea Sharon, Anna Sajina, Mark Sargent, Fabian Walter

history of the universe



z~1000
0.0003 Gyr

z~15-1000
0.0003-0.3 Gyr

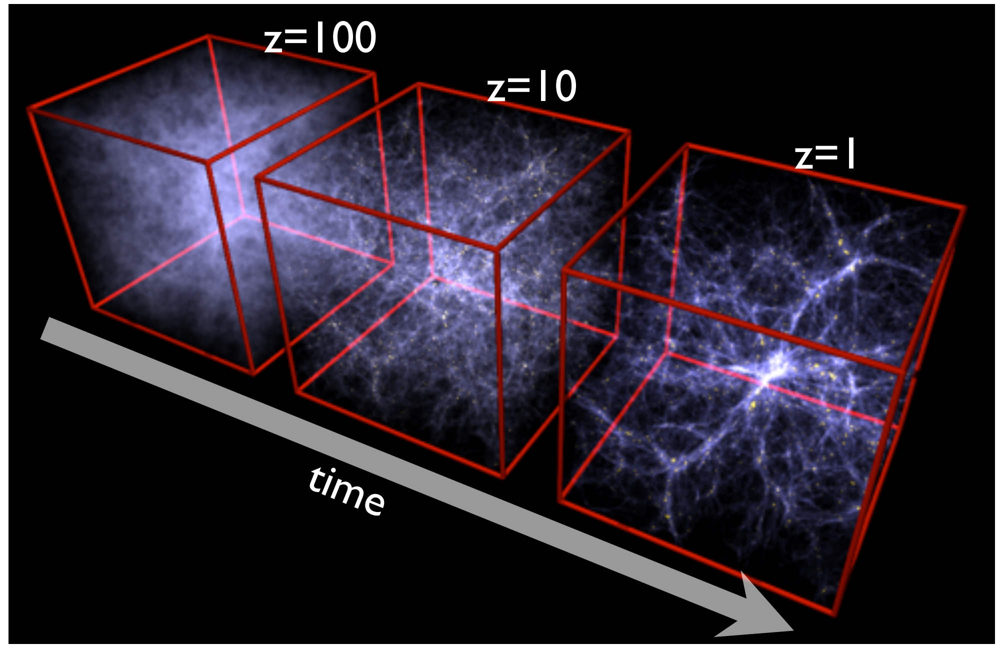
z~6-15
0.3-1 Gyr

z<~6
>1 Gyr

z~0
13.8 Gyr

theoretical framework

Hydrodynamical simulations of cosmic structure formation



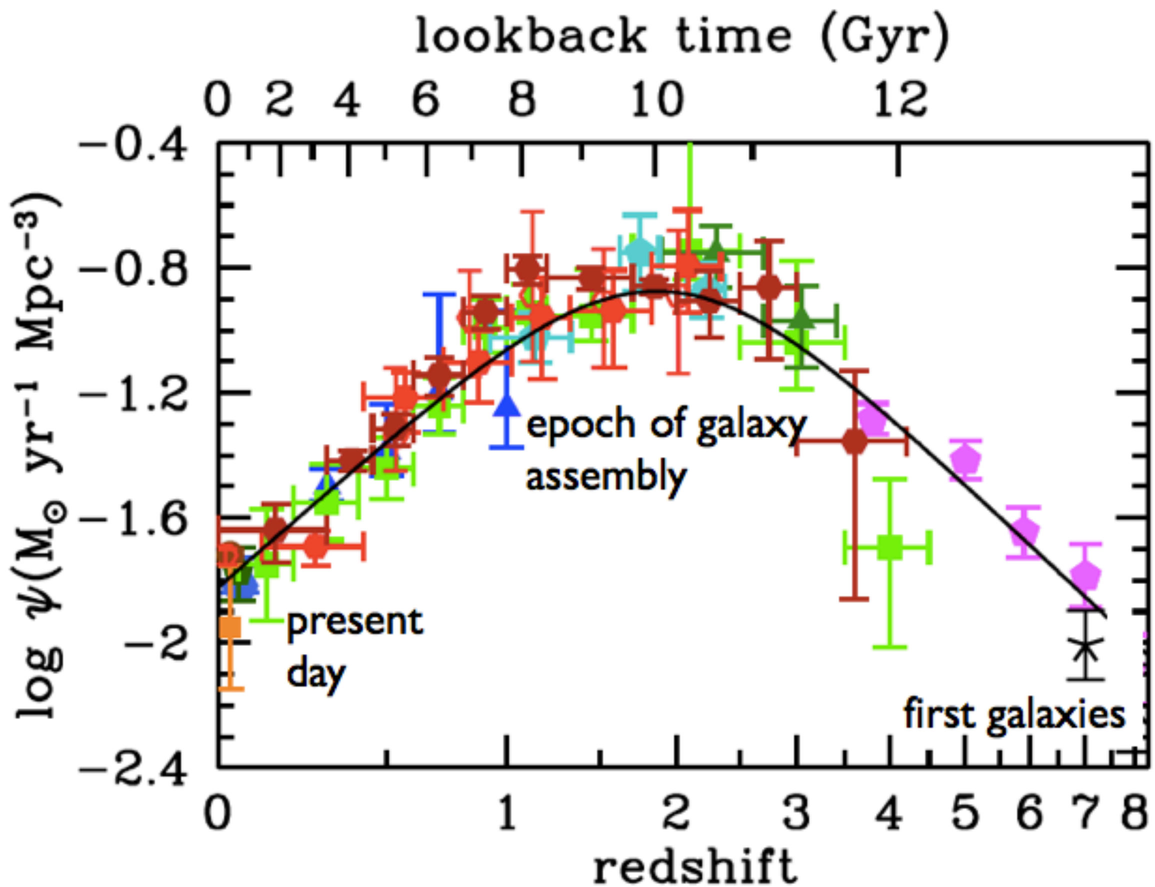
e.g. GADGET, AREPO, Springel et al.

Galaxy growth through gas accretion and mergers...

...but the *gas supply/conversion* is largely unconstrained observationally, especially at z>5 (the first billion years)

cosmic star formation

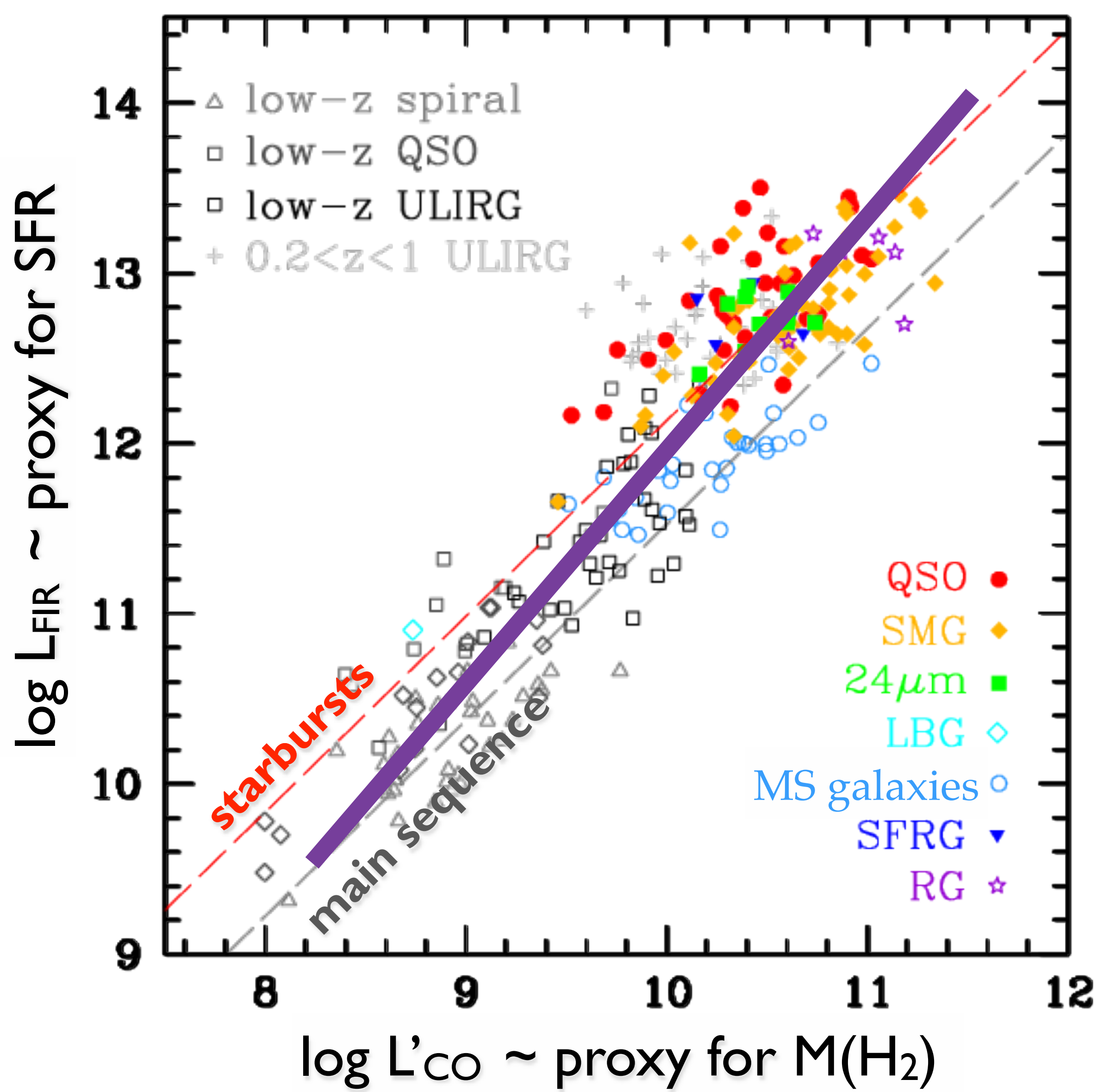
Volume density of star formation in galaxies as f(cosmic time)



Madau & Dickinson, ARA&A 2014

early work: Madau et al. 1998, Steidel et al. 1999

Kennicutt-Schmidt Relation: The ISM drives Star Formation



Simplest Version of "Star Formation Law": Spatially Integrated Observables

L'_{CO} vs. L_{FIR}

as a surrogate for

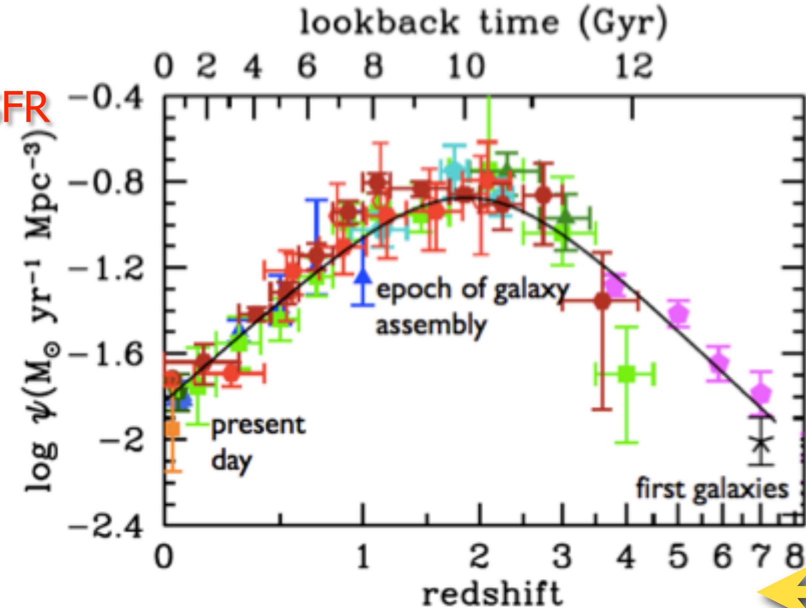
M_{gas} vs. SFR

One super-linear relation or
Two sequences (*quiescent/starburst*)
Bimodal or running *conversion factor*

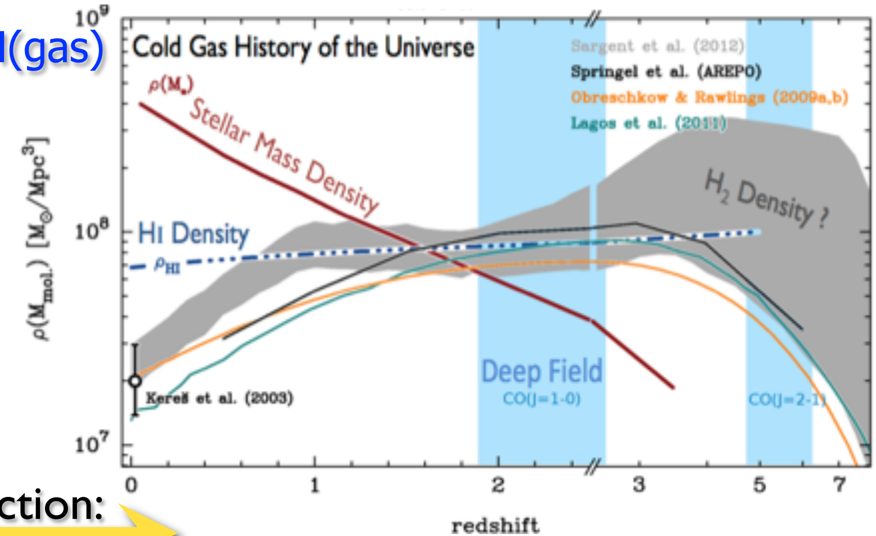
…many subtleties, but:
High-z galaxies higher on *both* axes
Quiescent *and* Starburst Galaxies

Carilli & Walter 2013 ARAA; after Daddi et al. 2010, Genzel et al. 2010 *cold gas history of the universe:* the "missing half" of galaxy evolution

Ω_{SFR}



$\Omega_{M(gas)}$



connection:
star formation law (M_{gas} vs. SF rate)

Star formation law:
SF history of the universe is a reflection of the cold gas history of the universe (gas supply)

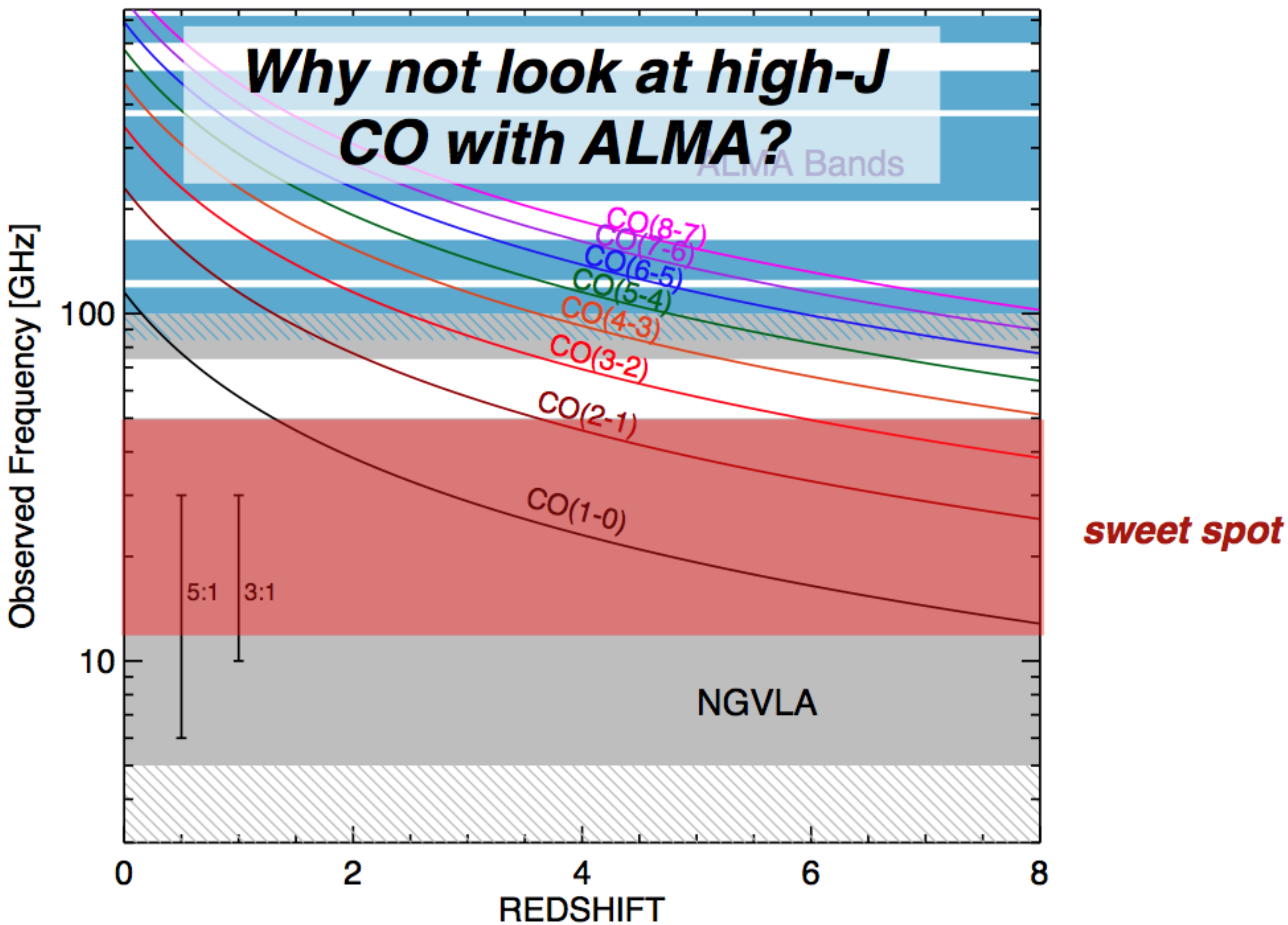
⇒ Studies of galaxy evolution are shifting focus to cold gas (source vs. sink)

⇒ Epoch of galaxy assembly = epoch of gas-dominated disk galaxies?

Problem: populations at high-z so far are highly selected (IR, radio, UV/optical luminosity)
⇒ may miss cold gas rich, quiescent galaxy populations

solution: unbiased census of molecular gas, the fuel for star formation
i.e. a **molecular deep field** – at the same time: detailed imaging of gas & dust

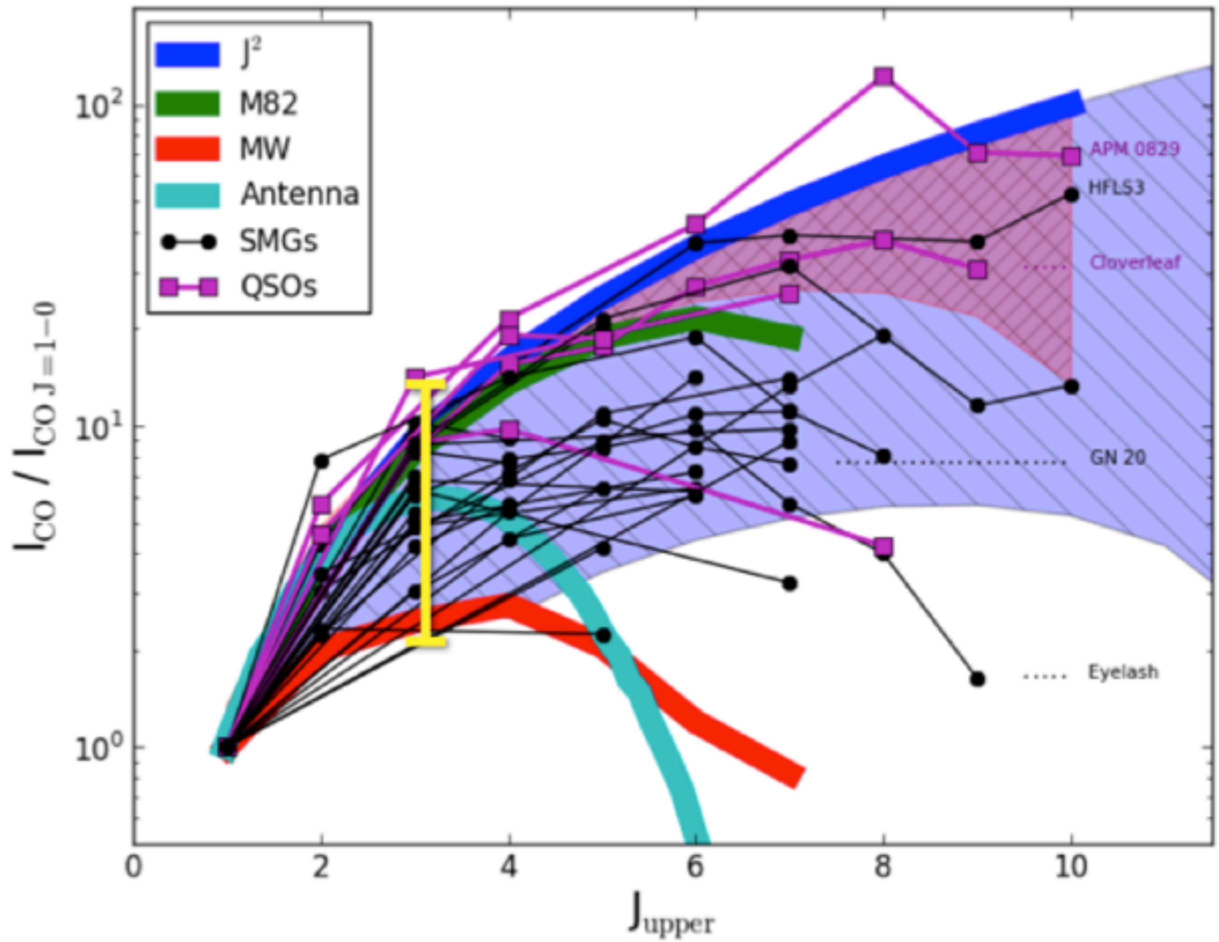
CO: probing H_2, star-forming gas



WG3 White Paper

Low-J CO is critical

Need low-J CO due to variation in CO excitation ladder: diverse SLEDs at high-z!

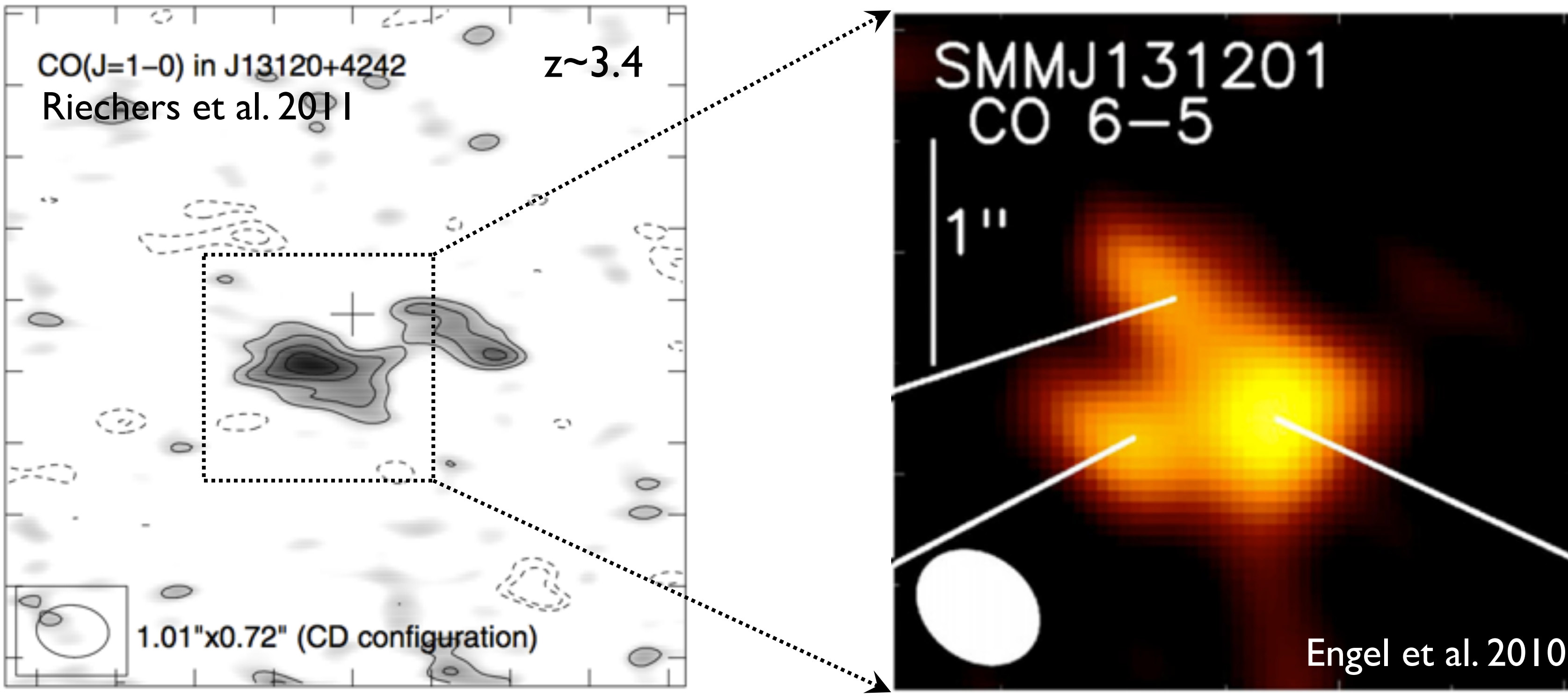


Factor of ~3-8 variation in $I_{CO(3-2)}/I_{CO(1-0)}$ translates to same uncertainty in M_{H_2} (even without α_{CO} uncertainty taken into account, which is ~5)

Casey, Narayanan & Cooray (2014) Phys Rep.

Low-J CO is critical:

Observational Perspective

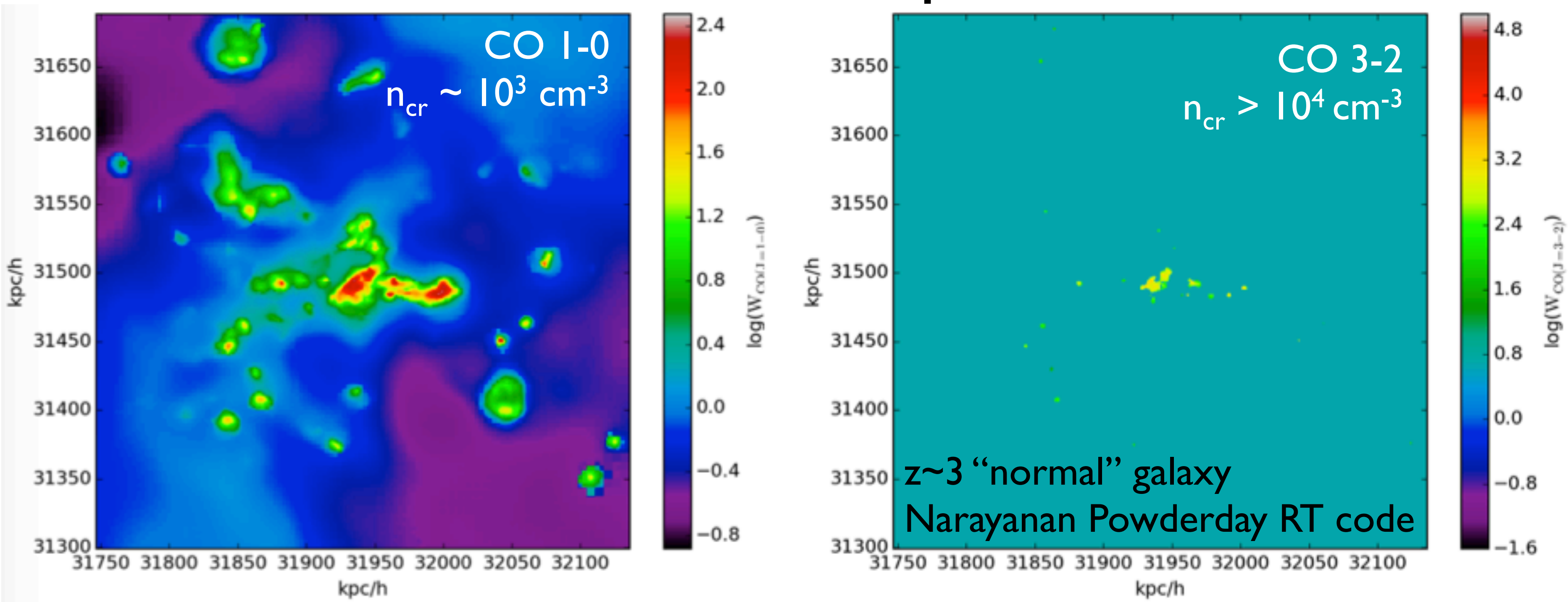


Observations: CO J=1-0 can be significantly more spatially extended spatially and in velocity than high-J CO emission

⇒ full molecular gas reservoir (low-J) vs. only highly-excited gas in dense, actively star-forming clouds (high-J)

Low-J CO is critical:

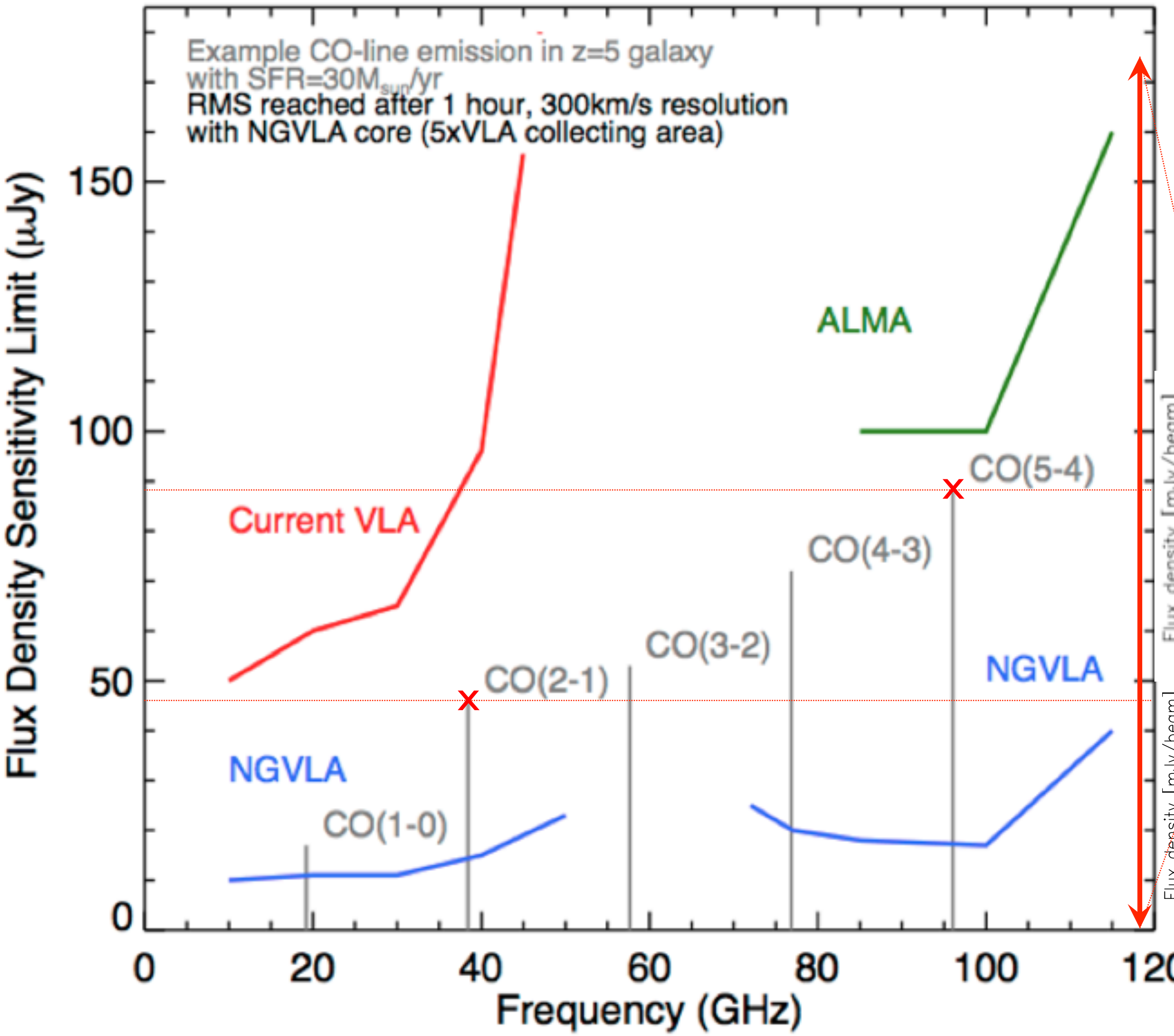
Simulations Perspective



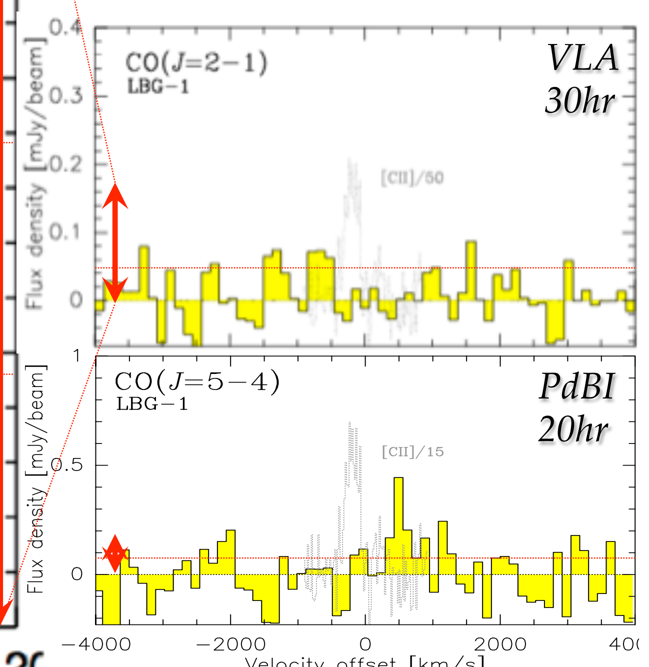
Galaxy Assembly: ngVLA CO imaging at <1 kpc resolution

- Low-J CO: large-scale gas dynamics, not just dense cores
- w. ALMA dust imaging: resolved star formation laws

Sensitivity: detectability for z=5 galaxy



Example:
z=5.3 “normal” galaxy
Lyman-break selected
SFR_{UV} = 22 M_{sun}/yr

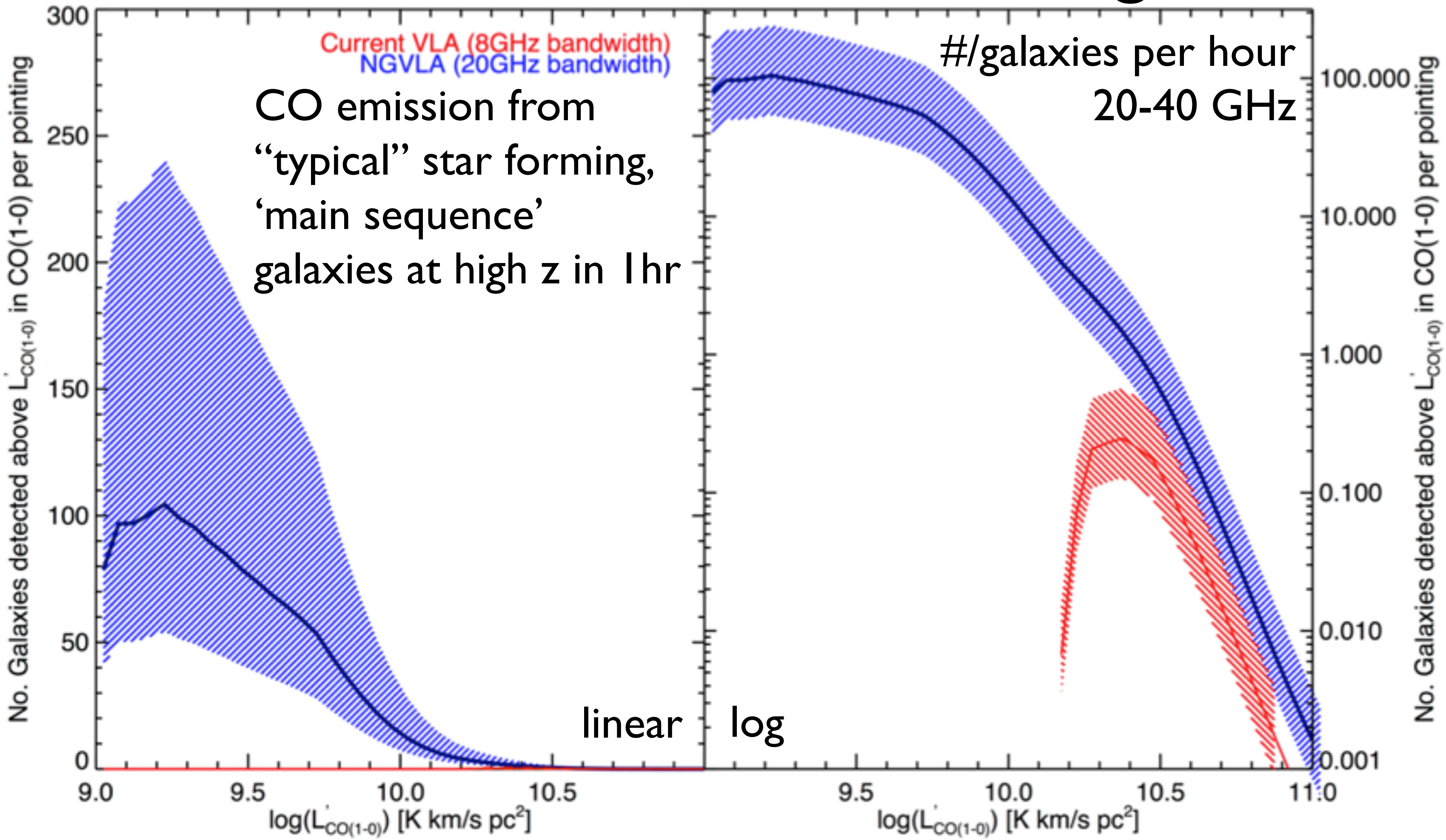


Riechers et al. 2014b,16

Demonstration for ngVLA Surveys: VLA Molecular Deep Field Survey

COLDz (PI: Riechers): 300 hr "Blind" CO survey in COSMOS & GOODS-N survey fields
→ detect few 10s of candidate "normal" z=2-3 galaxies in CO(1-0), typ. gas masses $>10^{10}$ M_{sun}
→ detect several z=5-6 galaxies in CO(2-1), but limited to massive dusty starbursts

New horizon in molecular cosmological surveys



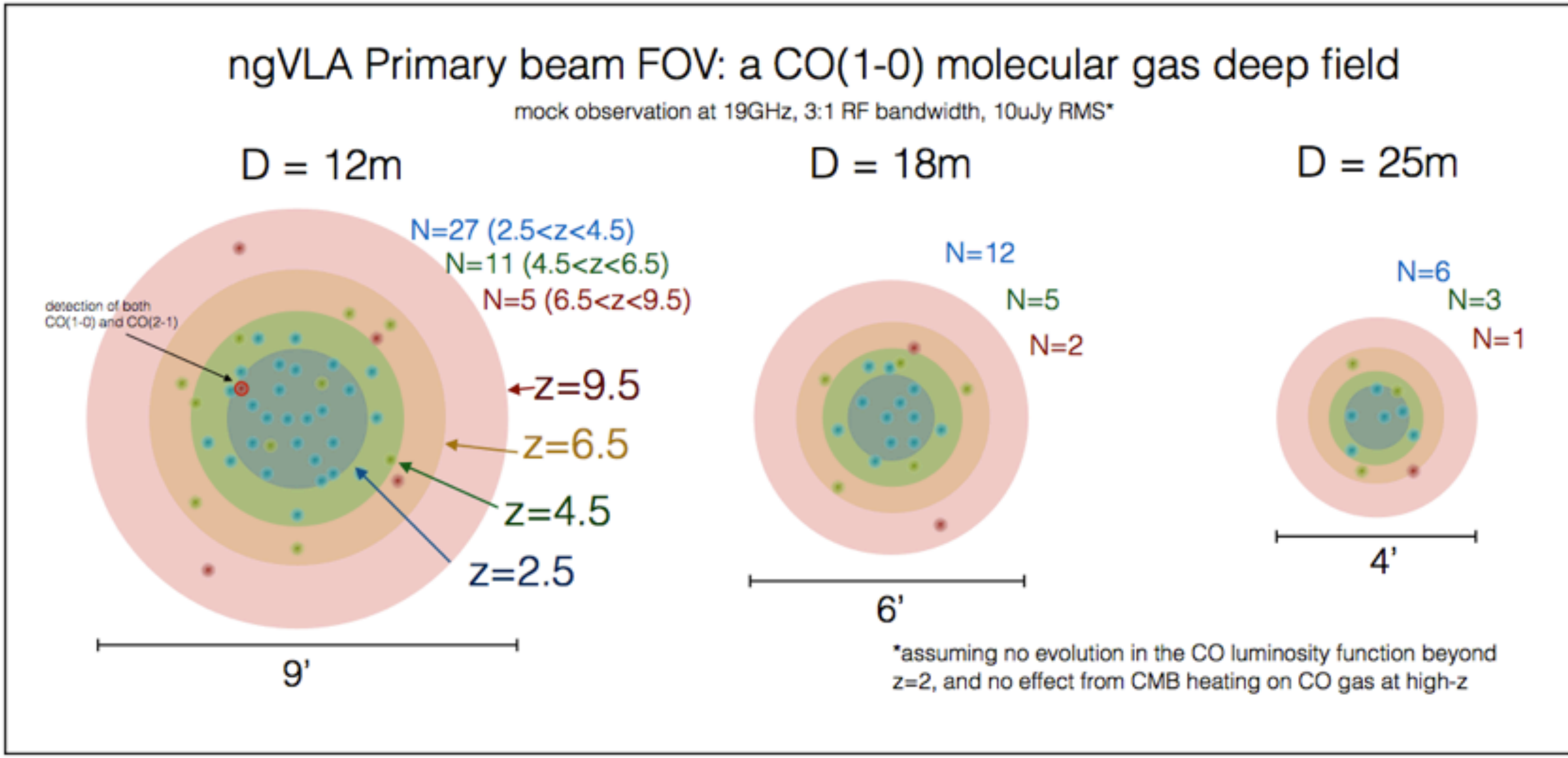
Increased sensitivity & BW => dramatic increase molecular survey capabilities.

JVLA: ~0.1 – 1 CO galaxies/hr, $M_{gas} > 10^{10}$ M_{sun}

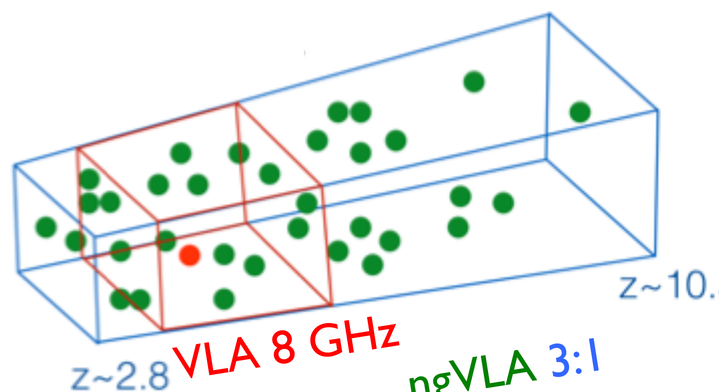
ngVLA: 10s – 100s CO galaxies/hr, $M_{gas} > 2 \times 10^{9}$ M_{sun}

1000 hours: cover ~1sq deg down to ~10M_{sun}/yr → ~200,000 galaxies

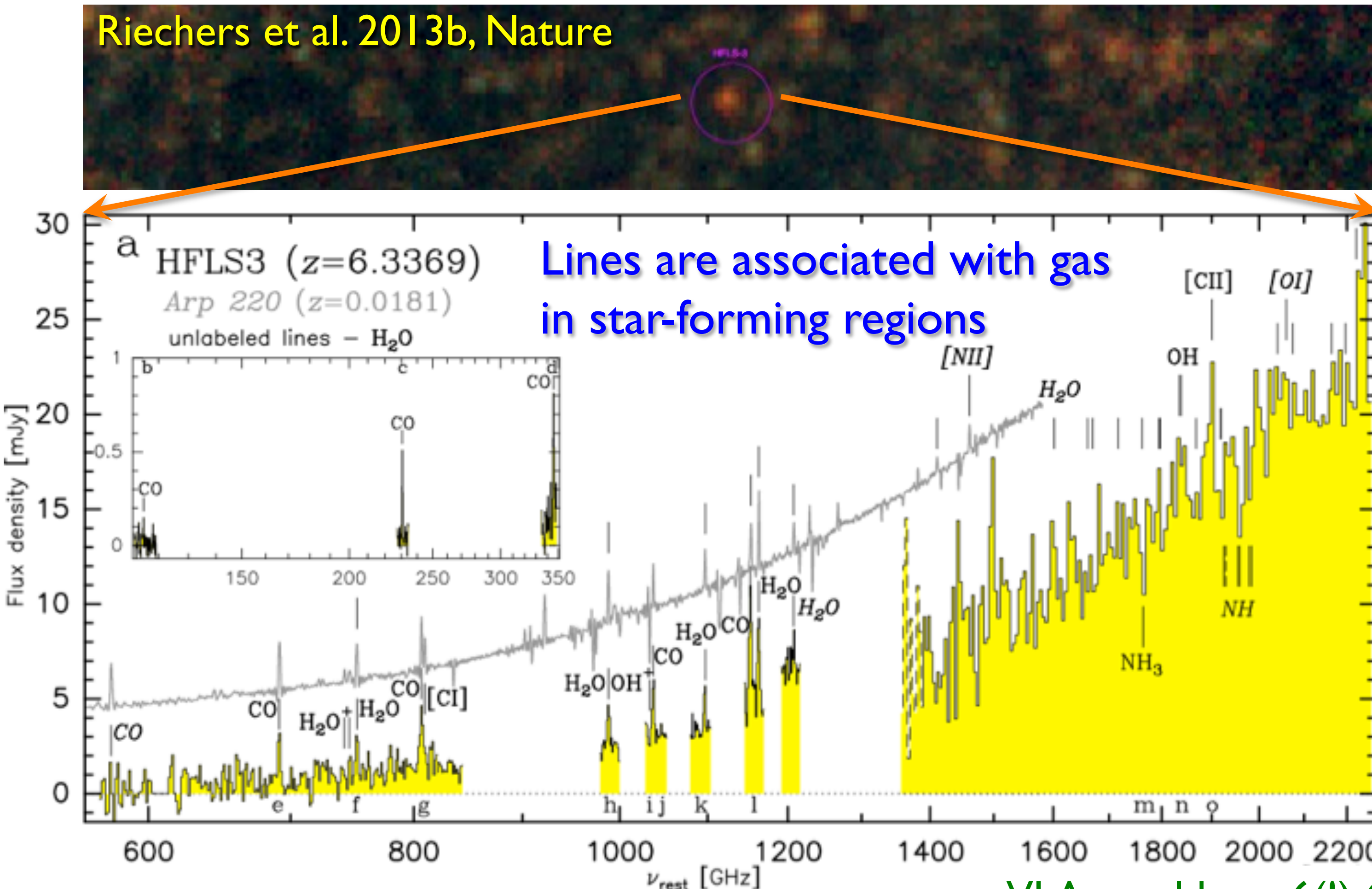
ngVLA vs. CO Deep Fields: Antenna Size



smaller antennas at fixed collecting area results in higher detection rates
(besides better uv-coverage/ dynamic range)



CO as a redshift beacon



Dusty Massive Starburst HFLS3:

Galaxy confirmed … at z=6.3369 !!

Detect
7 CO lines
7 H_2O lines
H_2O^+
NH_3 (absorption)
OH
OH^+ (absorption)
[CI]
[CII]
Hints of others…
⇒ Highly enriched

ngVLA would see 6(!) CO lines & H_2O/[CI] in a matter of *minutes*

how common are such sources?

→ typically missed by optical/IR surveys due to dust obscuration

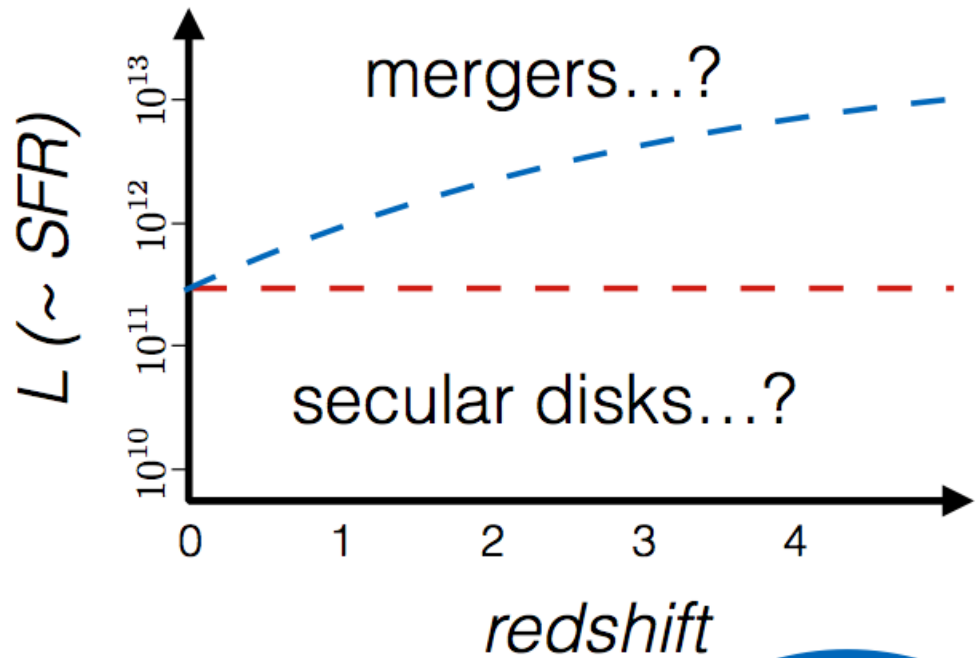
→ ~50% of dusty starburst REQUIRE CO/fine structure line redshifts, since they are missed even by the most sensitive optical spectroscopic surveys (Chapman, Casey)

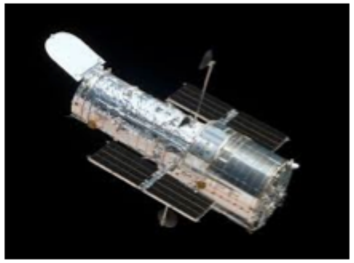
Mergers or secular disks?

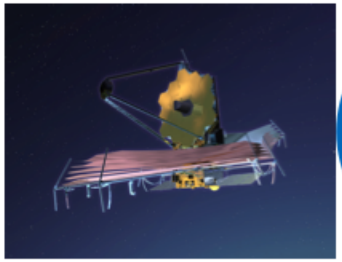
What role do **mergers** have in early Universe galaxy formation?

Locally, all with $L_{\rm IR} > 10^{11.5} L_\odot$ are mergers, but very rare.
At high-z, are mergers more prominent?

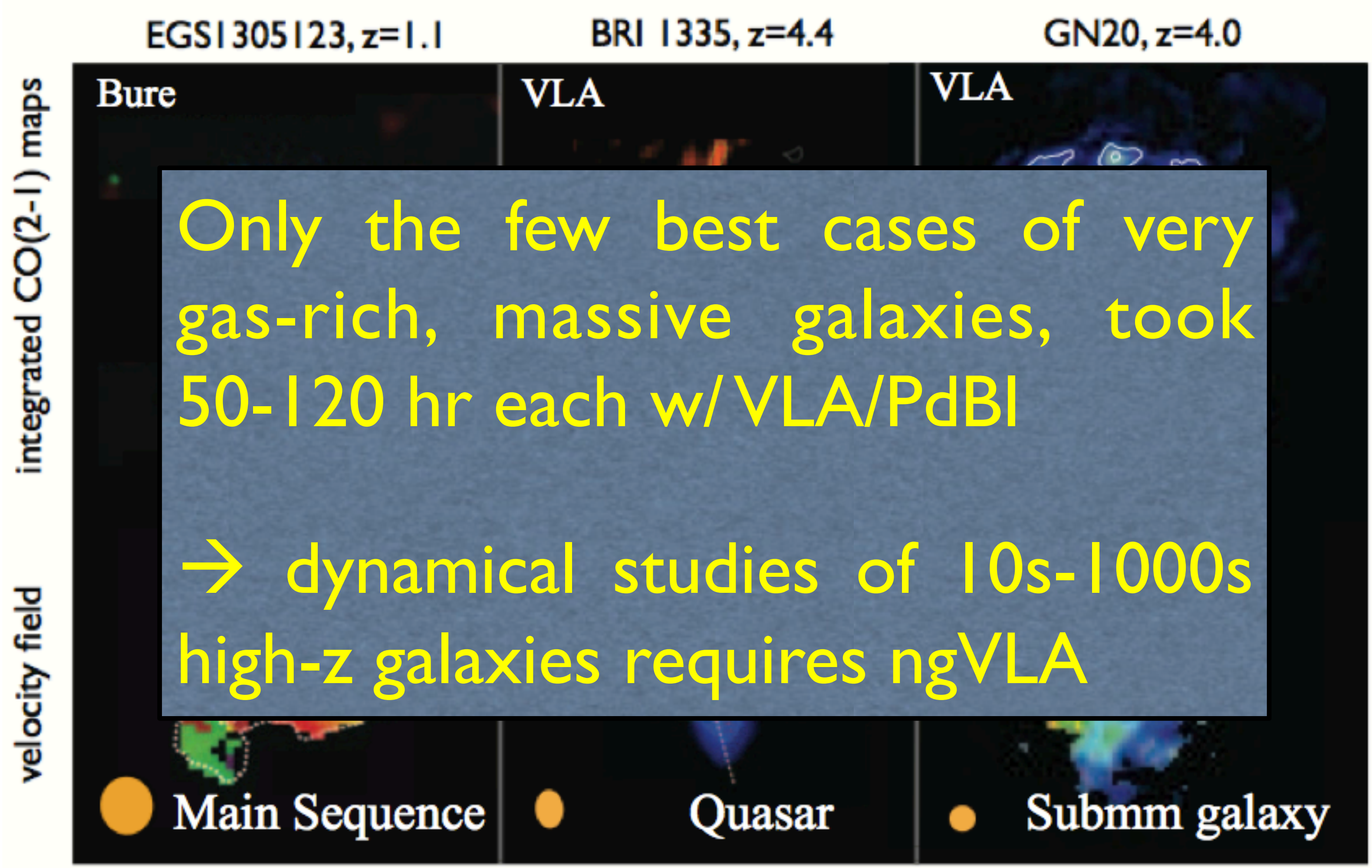
Important to probe moderate SFR regime at z>2: impossible with Hubble Space Telescope morphologies because:
(a) Optical light redshifted out of range (wait for JWST), and
(b) DUST (80-95% of luminosity emitted by gas/dust, not direct starlight)
(c) Kinematics!







some resolved imaging



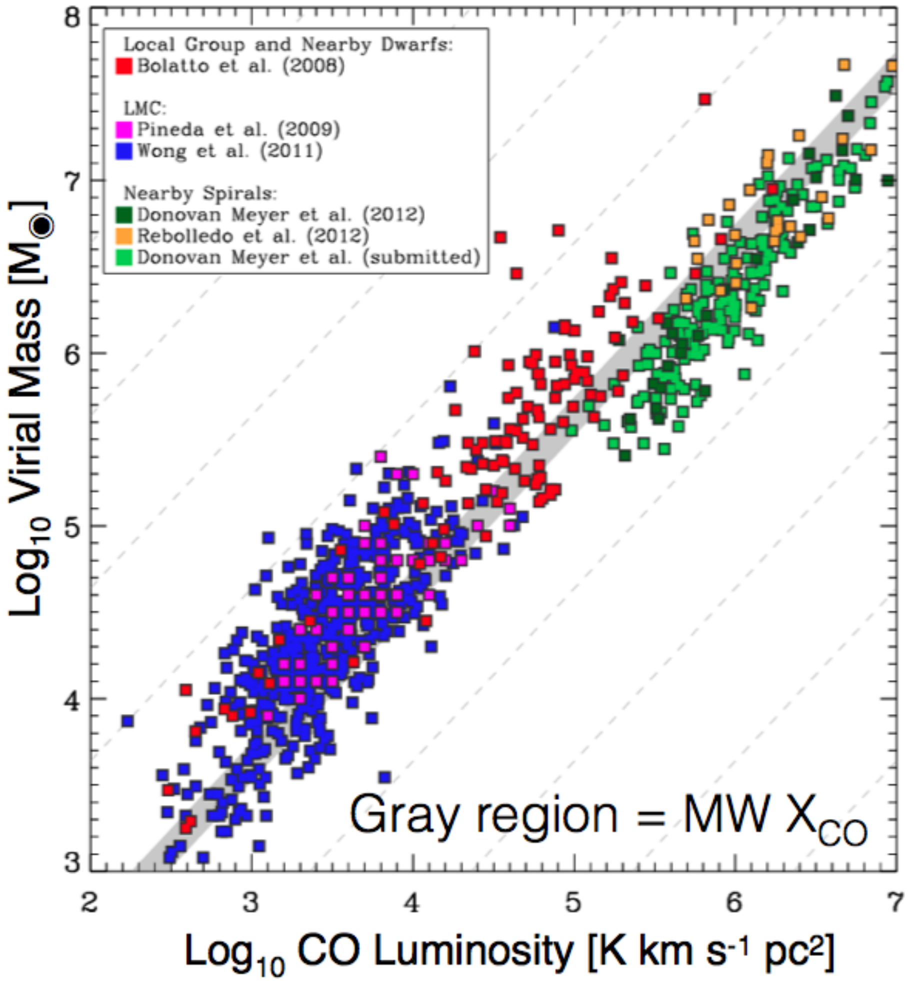
Only the few best cases of very gas-rich, massive galaxies, took 50-120 hr each w/ VLA/PdBI

→ dynamical studies of 10s-1000s high-z galaxies requires ngVLA

Riechers et al. 2008; Tacconi et al. 2010; Hodge et al. 2012

- MSG: SFR $\leq 10^2$ M_o/yr, $\rho \geq 10^{-4}$ Mpc^{-3}, clumpy, turbulent, rotating 10kpc disks
- Quasars: SFR $\geq 10^3$ M_o/yr, $\rho \leq 10^{-5}$ Mpc^{-3}, highly disturbed, chaotic CO
- SMG: SFR $\geq 10^3$ M_o/yr, $\rho \leq 10^{-5}$ Mpc^{-3}, Mixed bag: major mergers and large disks

Dynamics



Bolatto, Wolfire & Leroy 2013 ARA&A

$$M_{H2} = \alpha \times L'_{CO1\text{-}0}$$

Total molecular gas masses and the CO-to-H2 conversion factor (X_{CO}):

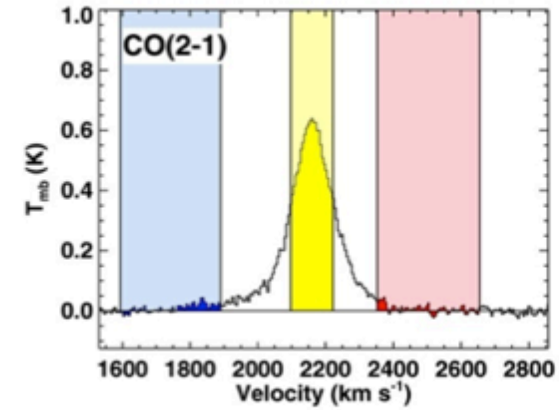
We currently have to extrapolate from what we know about local galaxies.

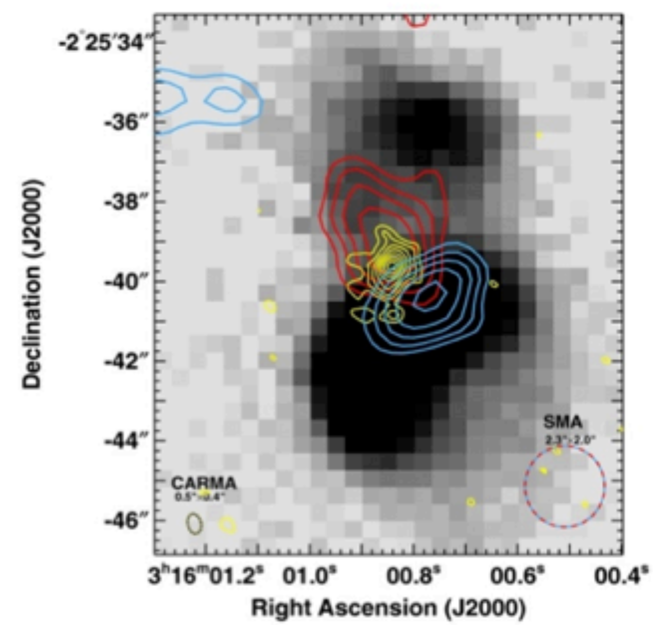
A Next Generation VLA is required to directly measure the conversion factor, and thus total gas masses, at high-z

Outflows, feedback and radio emission from radio-quiet AGN

Dynamics of molecular outflows – measure effect of AGN on ISM.

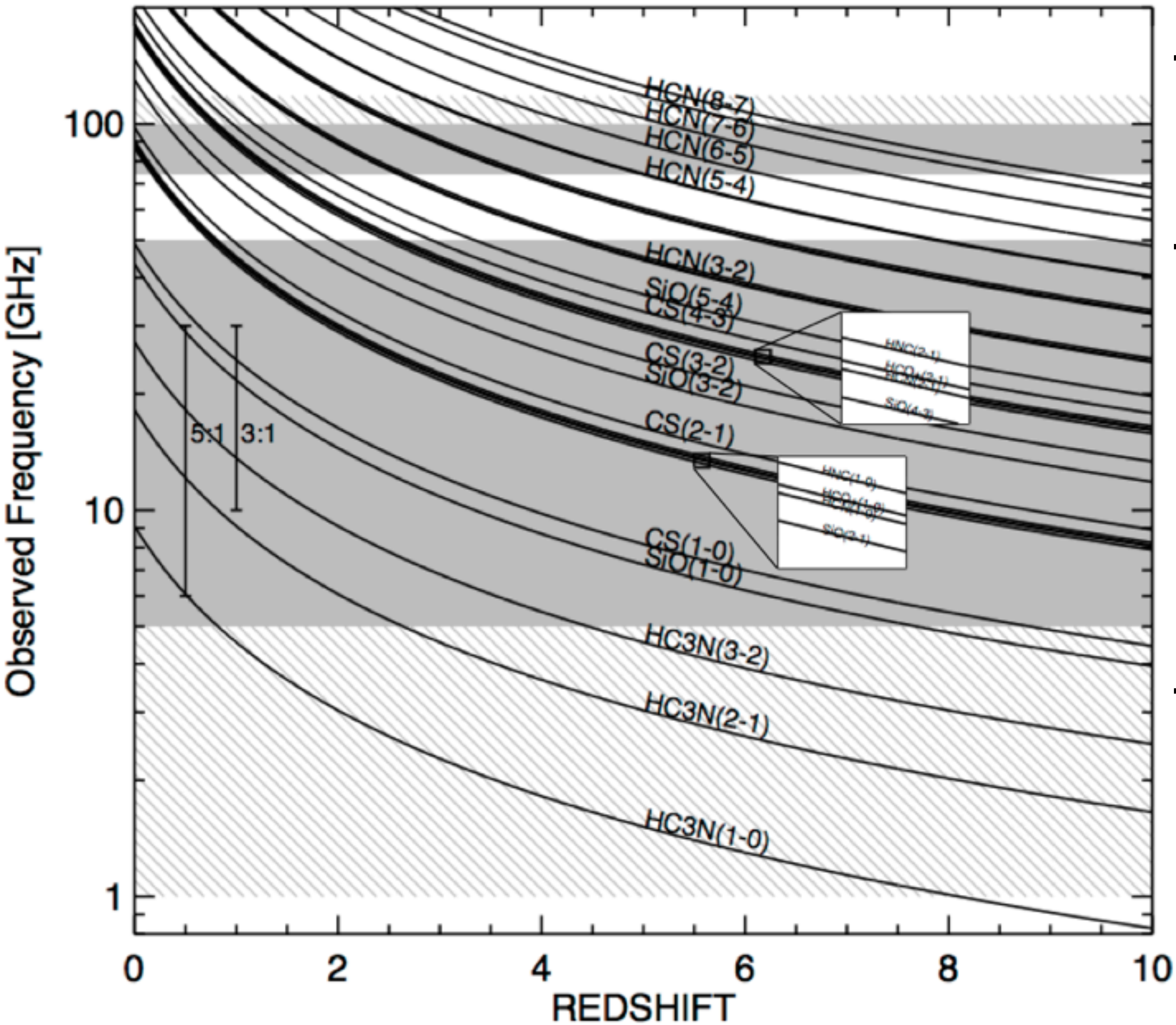
NG-VLA at ~100GHz - detailed studies of molecular gas (low-J CO, high density tracers, XDR vs PDR chemistry). Accurate measurements of molecular outflows.





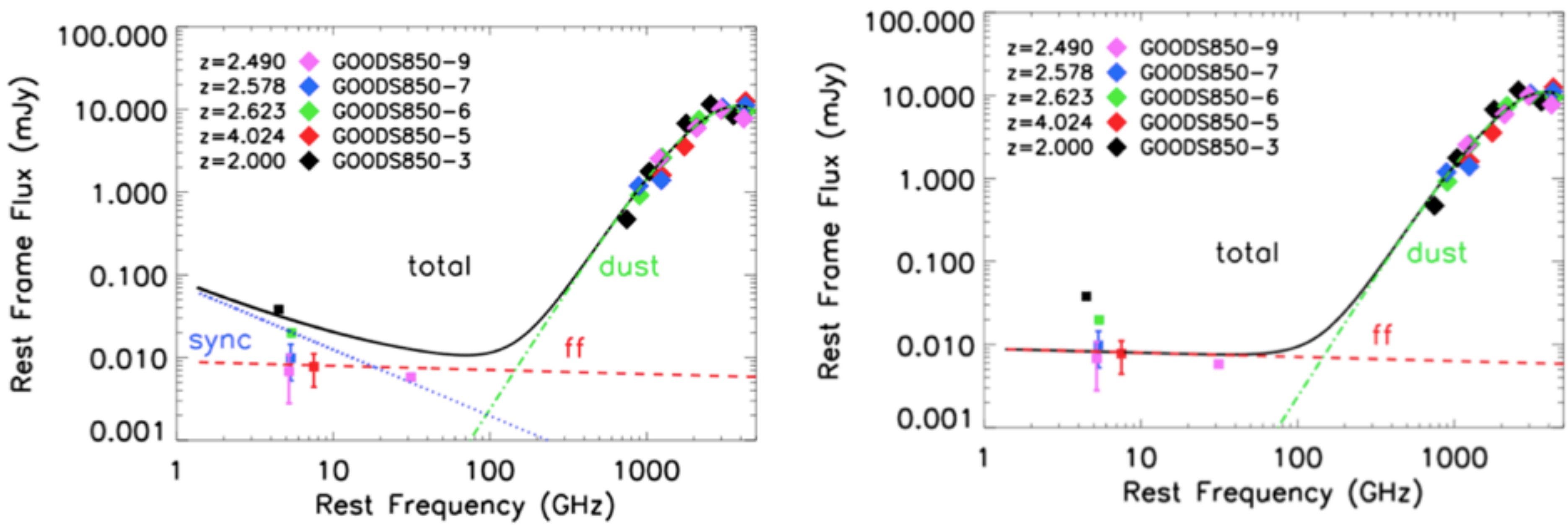
NGC1266: Alatalo et al. 2011, 2014 (CARMA/ALMA)

dense gas tracers



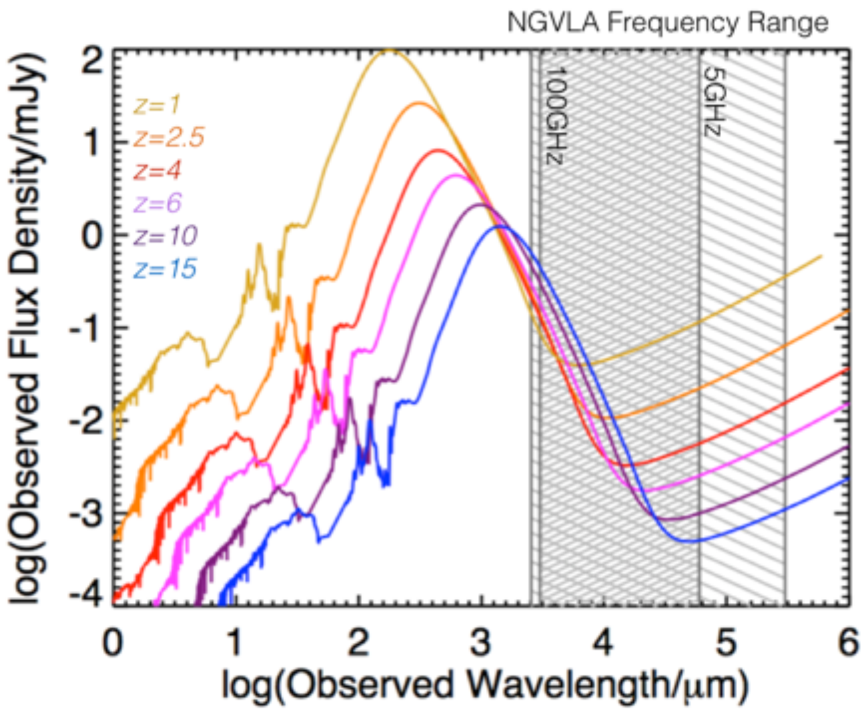
- probe dense, actively SF gas
- molecular chemistry/ metallicity evolution through cosmic times
- study impact of collisional vs. radiative excitation, shocks, etc.

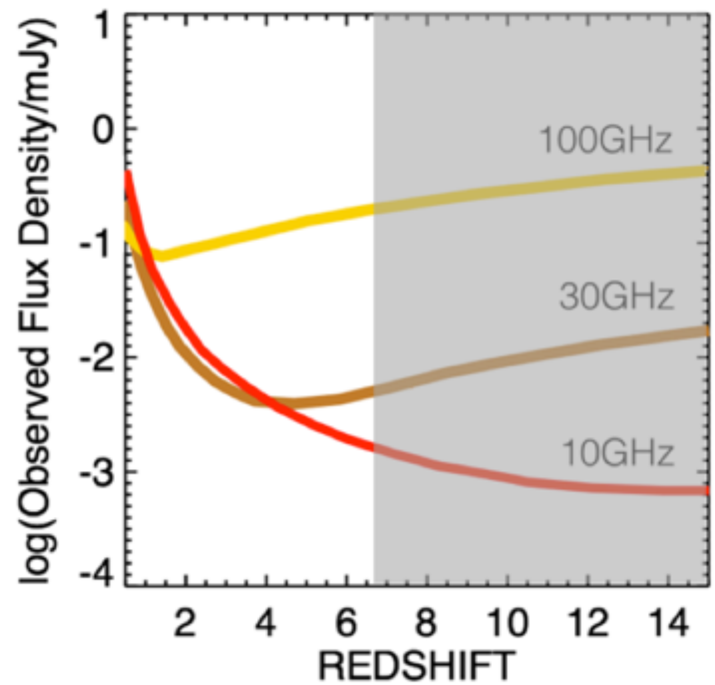
Continuum



CMB suppression of synchrotron in normal high-z galaxies: free-free directly proportional to # ionizing photons from massive stars: very accurate SFR indicator.

Continuum





At sufficiently high-redshift, ngVLA bands benefit from the *negative K-correction* on the cold dust Rayleigh-Jeans tail

As a consequence, ngVLA will provide important constraints on high-z dust continuum as well as cold gas

Summary

The ngVLA will critically enhance our view of galaxy evolution in the early universe, covering a broad range of line & continuum science

Critical aspects:

- broad bandwidth (most critical range: 15-50 GHz) – *large volume surveys in low-J CO, redshift confirmation, molecular chemistry*
- large collecting area (5-10x VLA) – *critical sensitivity to reach line luminosity limits where source densities are high, and out to* $z>5$
- large FoV – *filling collecting area with smaller antennas gives significantly enhanced survey speeds*
- high resolution (<100mas) – *critical to achieve sub-kpc resolution at* $z>2$ *and resolve gas disks and dynamics of nuclei…but sufficient collecting area on short baselines to retain surface brightness sensitivity towards few 10s K emission*