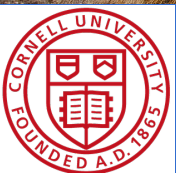
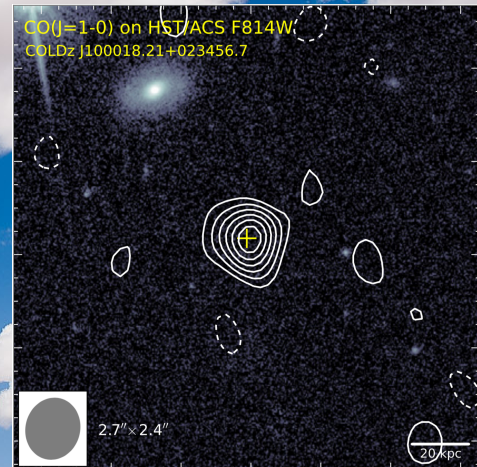


The VLA CO Luminosity Density at High Redshift (COLDz) Survey

Dominik A. Riechers
Cornell University

Developing the ngVLA Science Program Workshop
June 28, 2017



with the COLDz Survey Team:

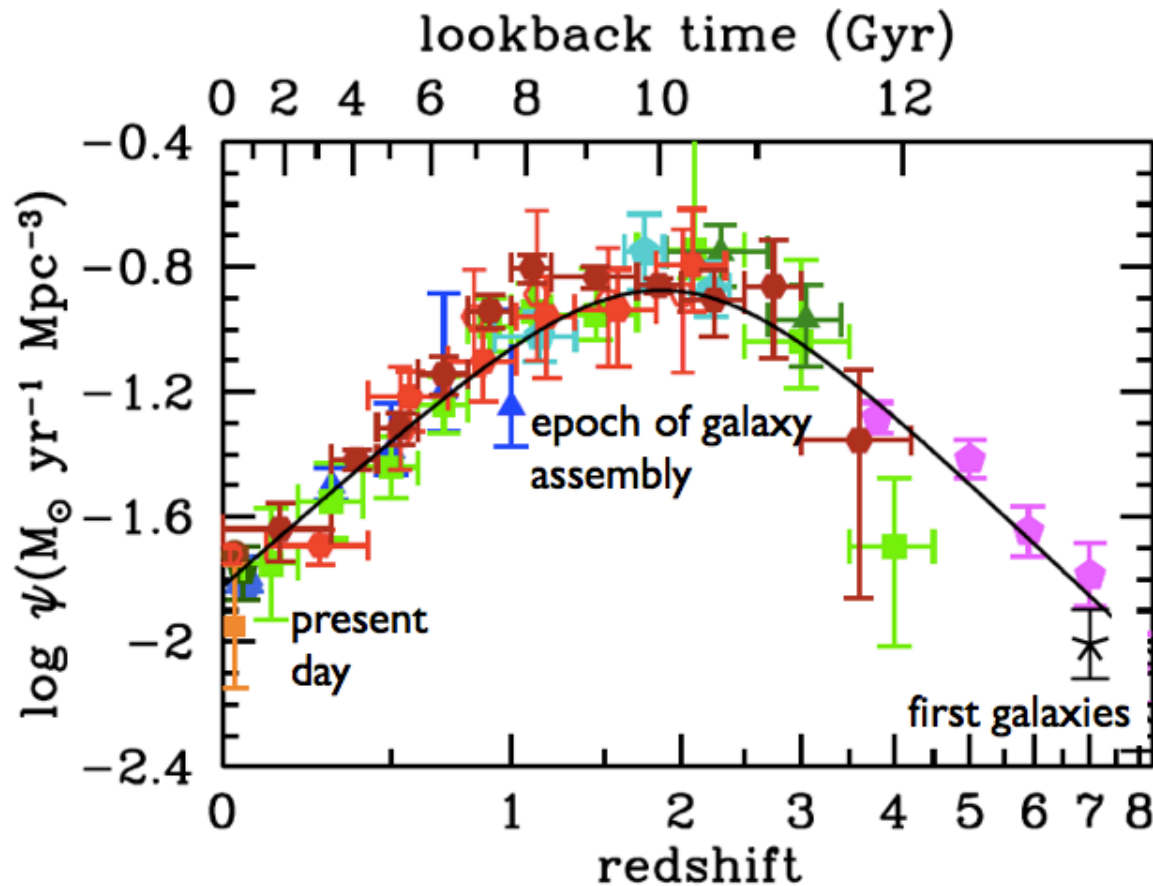
R. Pavesi (PhD), C. Sharon, F. Walter, C. Carilli, J. Hodge, M. Aravena, R. Decarli, P. Capak, E. da Cunha, E. Daddi, M. Dickinson, R. Ivison, M. Sargent, N. Scoville, I. Smail, V. Smolcic



National Science Foundation
WHERE DISCOVERIES BEGIN

cosmic star formation

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

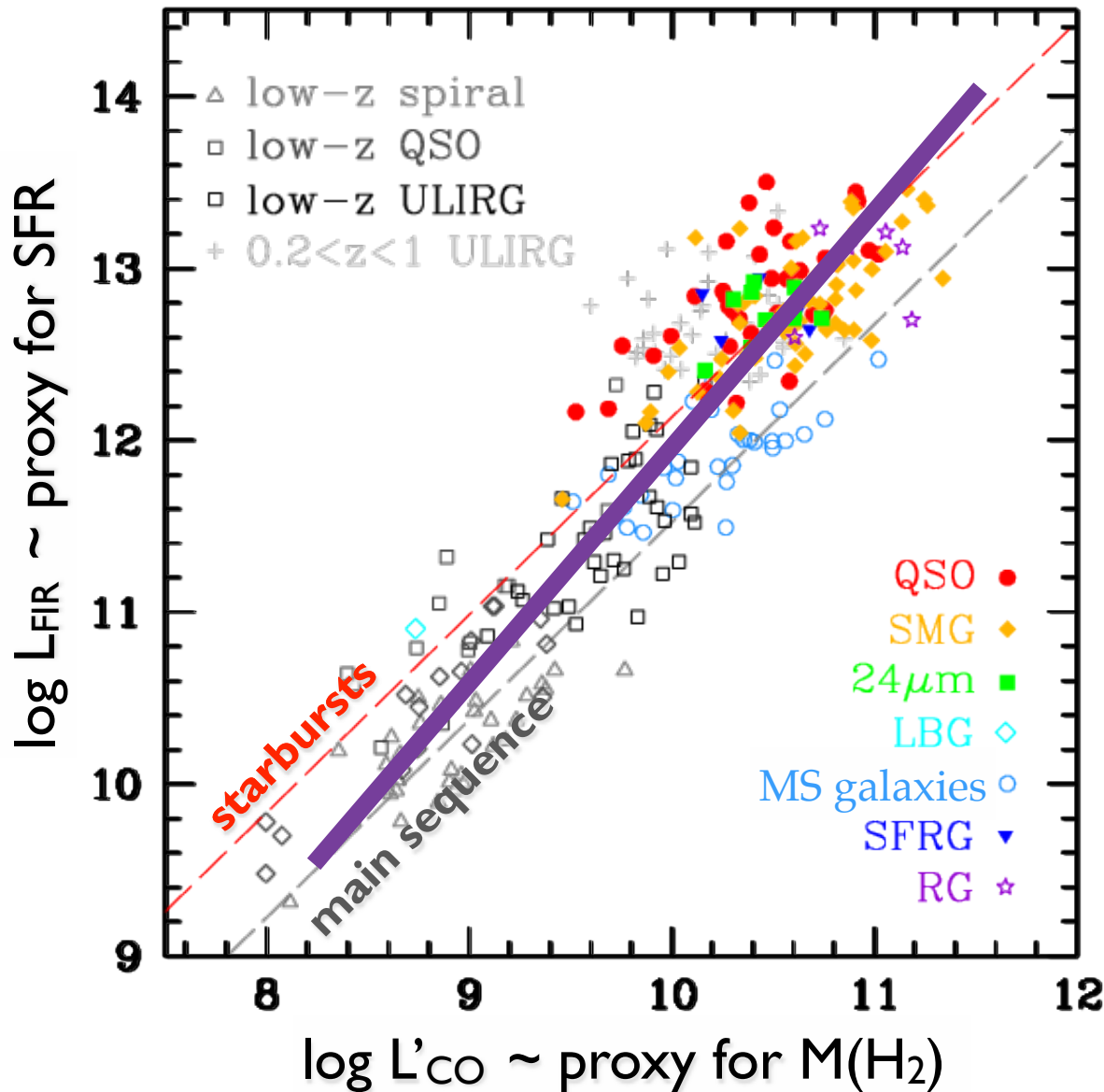


Madau & Dickinson, ARA&A 2014

→ What is the cause for this evolution?

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

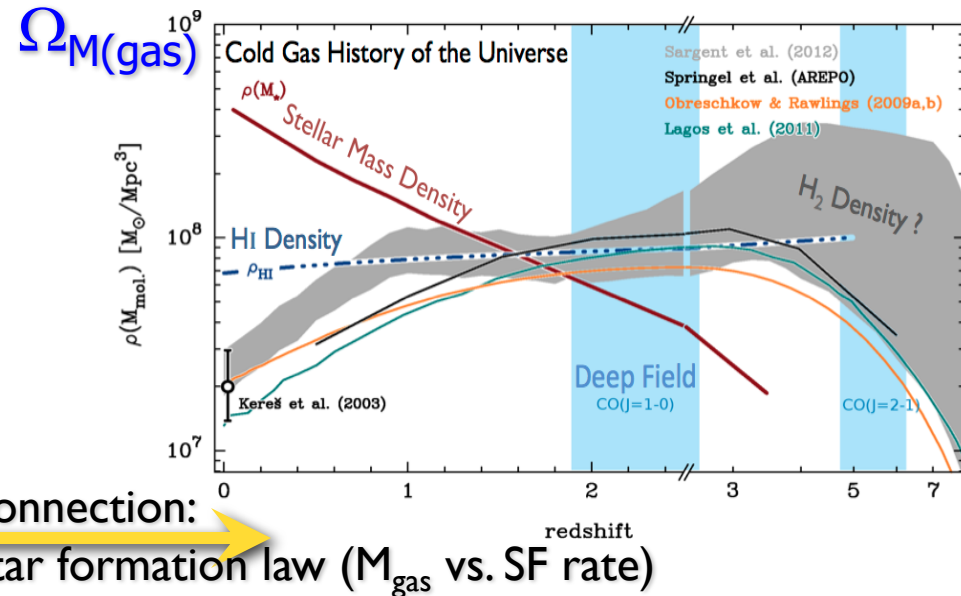
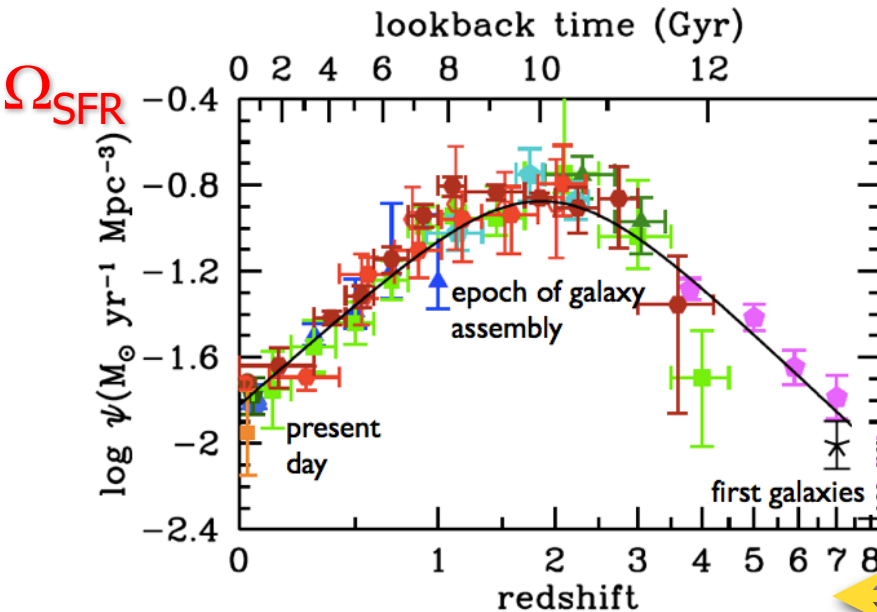
M_{gas} vs. SFR

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

cold gas history of the universe



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)

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: continuum deep field)

CO deep field surveys



1) PdBI Survey in Hubble Deep Field North (PI:Walter)

- 79-115 GHz (3mm), 180hr, $\sim 0.6 \text{ arcmin}^2$
- CO 1-0 @ $z=0.0-0.4$ & CO J=2-5 @ $z=1.0-6.2$
- $L'_{\text{CO}} > 8 \times 10^9 \text{ K km/s pc}^2$



2) VLA Survey in COSMOS & GOODS-North (PI: Riechers)

- 30-39 GHz (9mm), 320hr (main survey), $\sim 60 \text{ arcmin}^2$
- CO 1-0 @ $z=1.9-2.8$ & CO 2-1 @ $z=4.9-6.7$
- $L'_{\text{CO}} > 5 \times 10^9 \text{ K km/s pc}^2$ (deep)
- $L'_{\text{CO}} > 1.5 \times 10^{10} \text{ K km/s pc}^2$ (wide)

COLDz

3) ALMA Survey in Hubble Ultra Deep Field (PIs:Walter & Aravena)

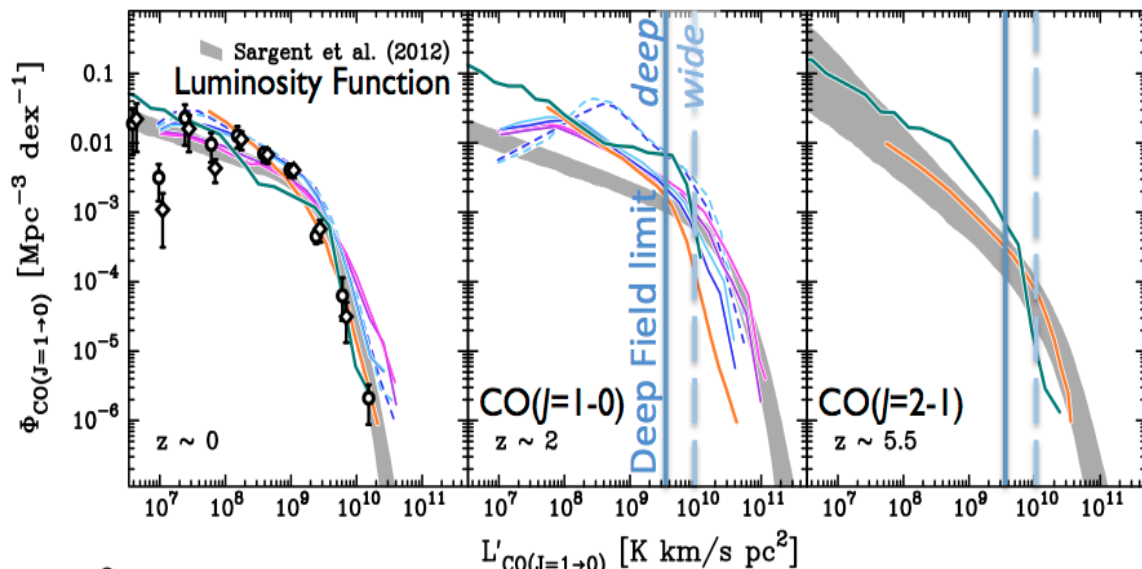
- 84-115 GHz (3mm) & 212-272 GHz (1mm), 40hr, $\sim 1 \text{ arcmin}^2$
- CO 1-0 @ $z=0.0-0.4$ & CO J=2-5 @ $z=0.0-5.8$
- $L'_{\text{CO}} > 3 \times 10^9 \text{ K km/s pc}^2$

-[CII] @ $z=6.0-8.0$

ASPECS-Pilot

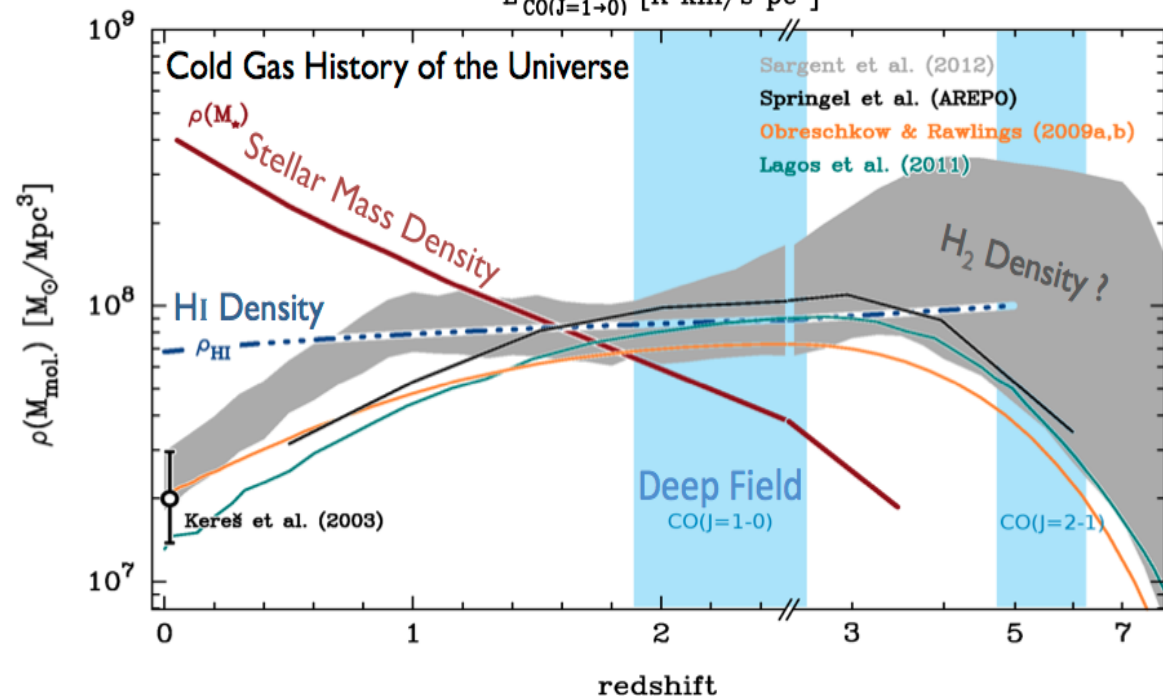


COLDz Molecular Deep Field: A Jansky VLA Large Program



CO luminosity function is only measured well at $z=0$ to date.

➤ Require very deep, wide-band line survey over substantial cosmic volume to measure *CO luminosity function* at high redshift



➤ $\text{CO} \rightarrow \text{H}_2$ mass: Obtain “Cold Gas History of the Universe”

CO excitation uncertain (e.g., factor 3-8 variation for $\text{CO } J=3-2$):
→ observe **CO $J=1-0$**

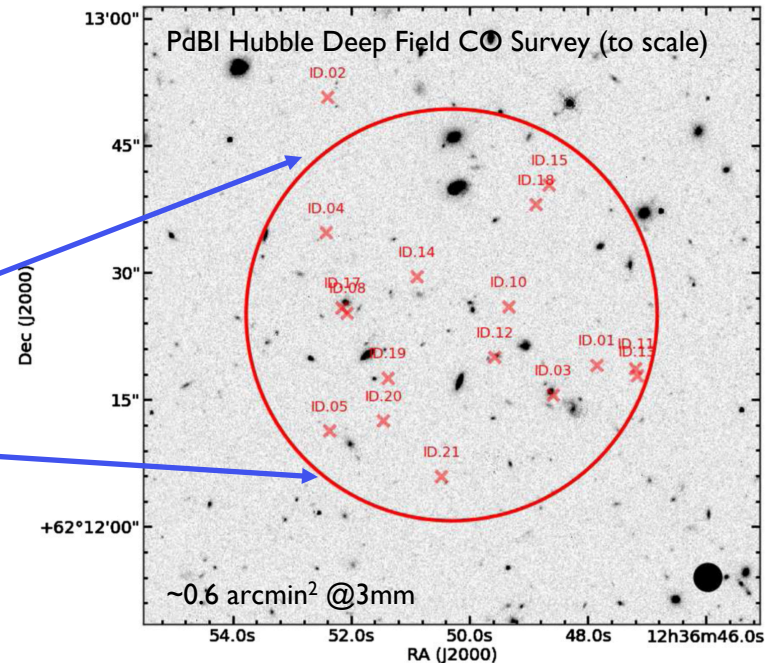
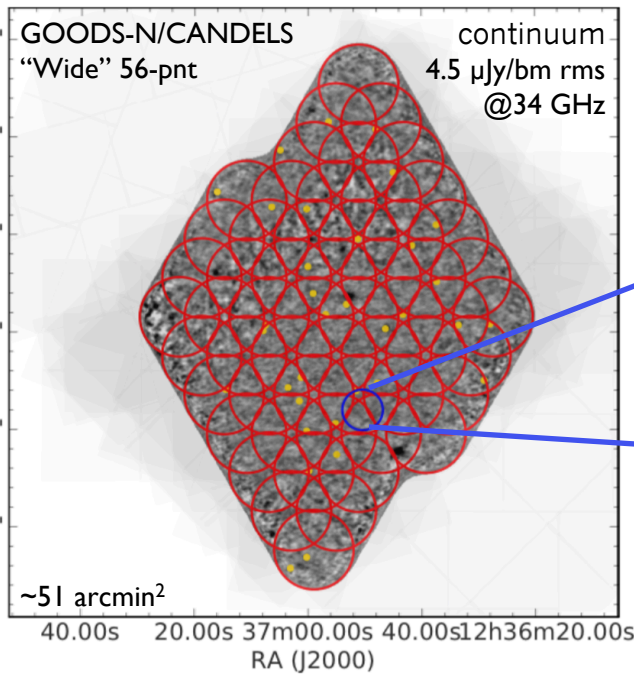
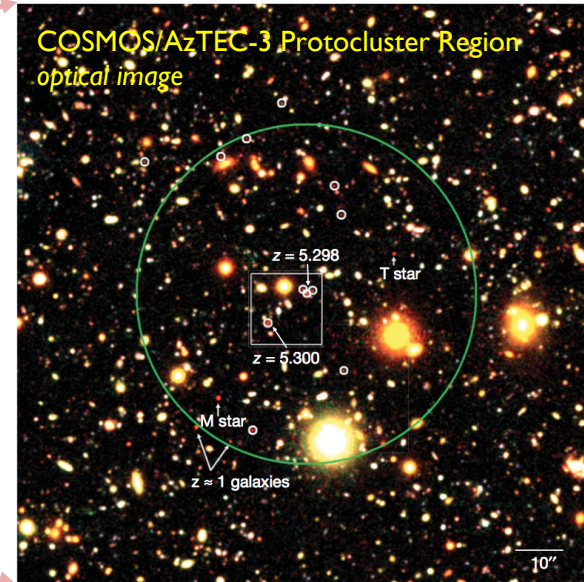
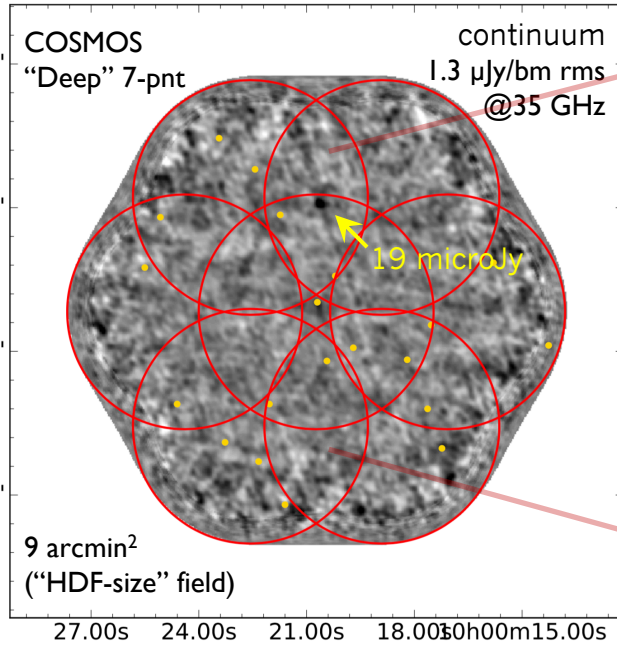
Only possible with the fully upgraded Karl G. Jansky VLA

➤ VLA Large Program (PI: Riechers)

R. Pavesi, PhD Thesis project

COLDz: A Jansky VLA Large Program

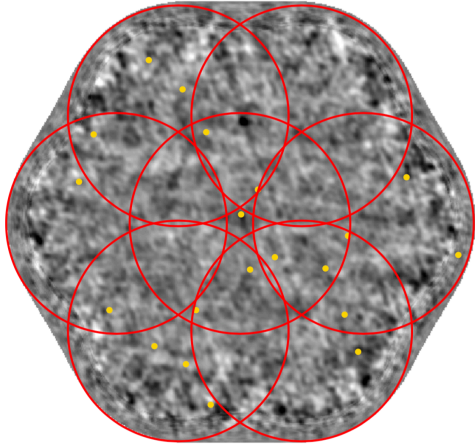
Pavesi, Riechers et al. 2017



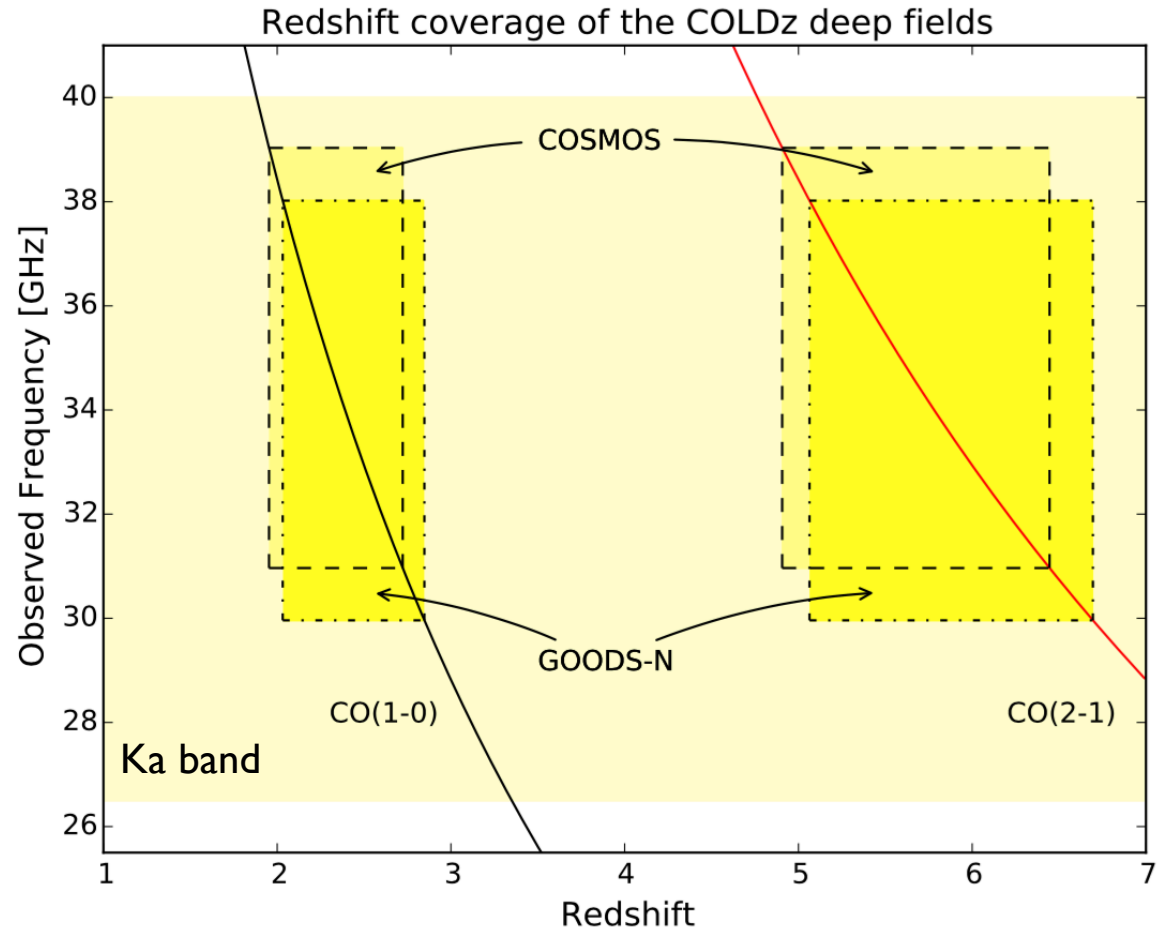
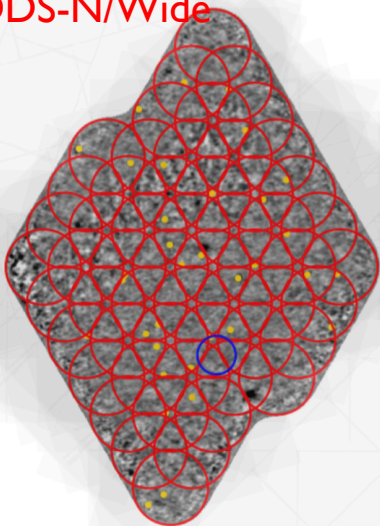
COLDz: “Blind” CO Redshift Range

Pavesi, Riechers et al. 2017

COSMOS/Deep



GOODS-N/Wide



One single 8 GHz wide frequency setup covers:

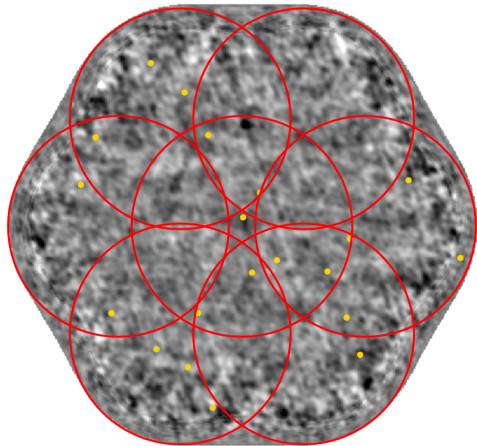
$CO(1-0)$ @ $z=1.9-2.8 \rightarrow >50,000 \text{ Mpc}^3$

$CO(2-1)$ @ $z=4.9-6.7 \rightarrow >320,000 \text{ Mpc}^3$

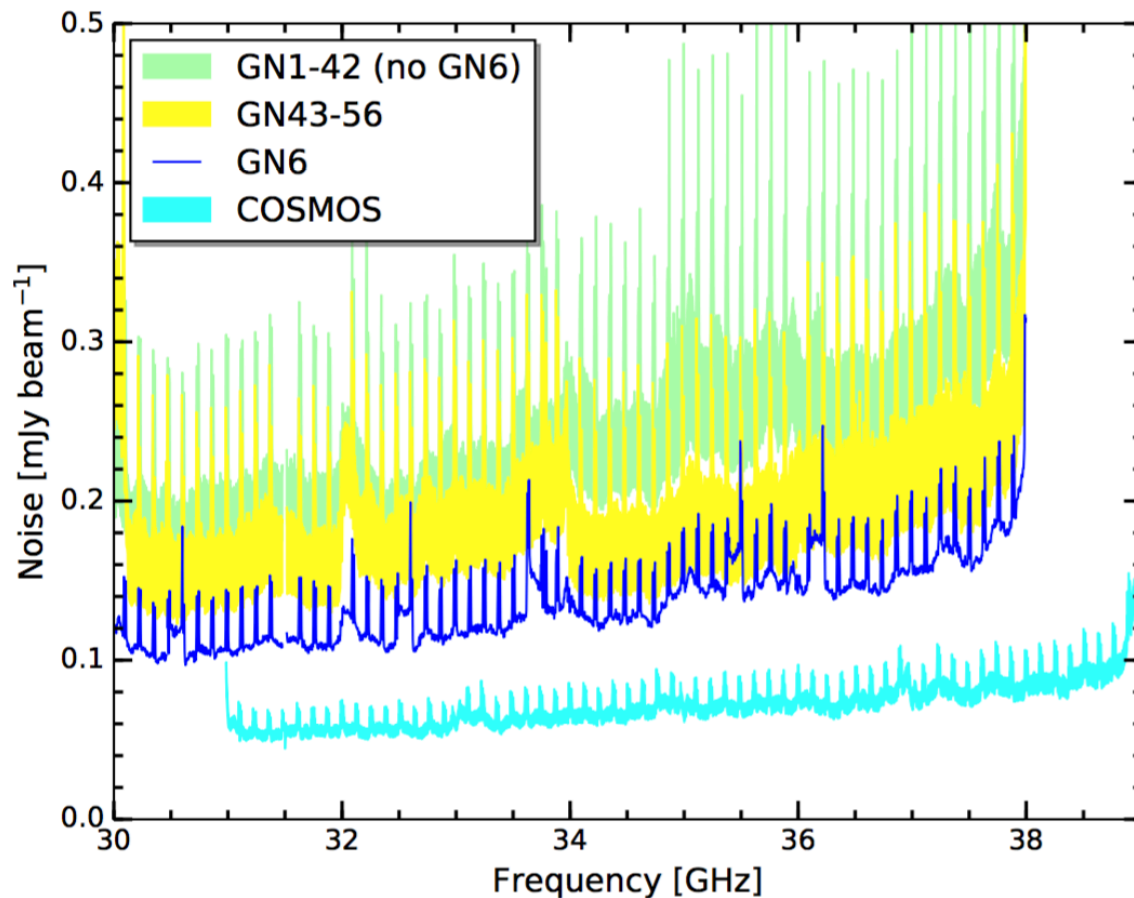
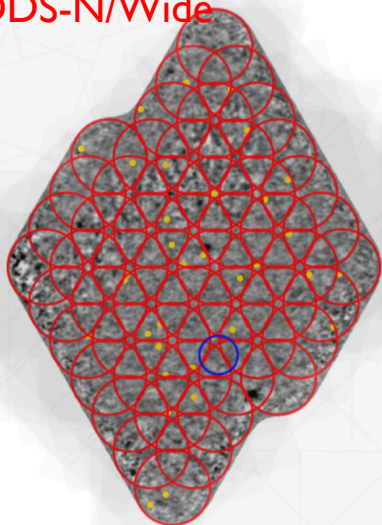
COLDz: Sensitivity

Pavesi, Riechers et al. 2017

COSMOS/Deep



GOODS-N/Wide



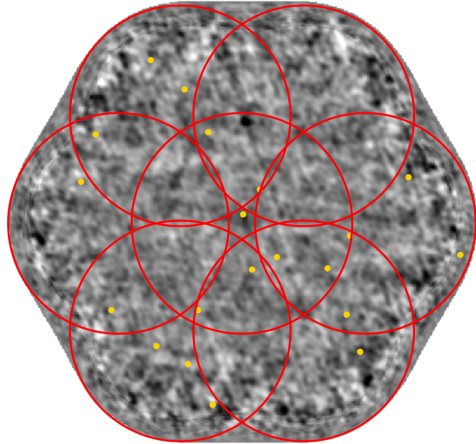
Approx. flat noise across bandpass
(slight increase at sub-band edges)

- GN6: deeper; contains original PdBI HDF pointing
- GN43-56: observed with upgraded 3-bit samplers

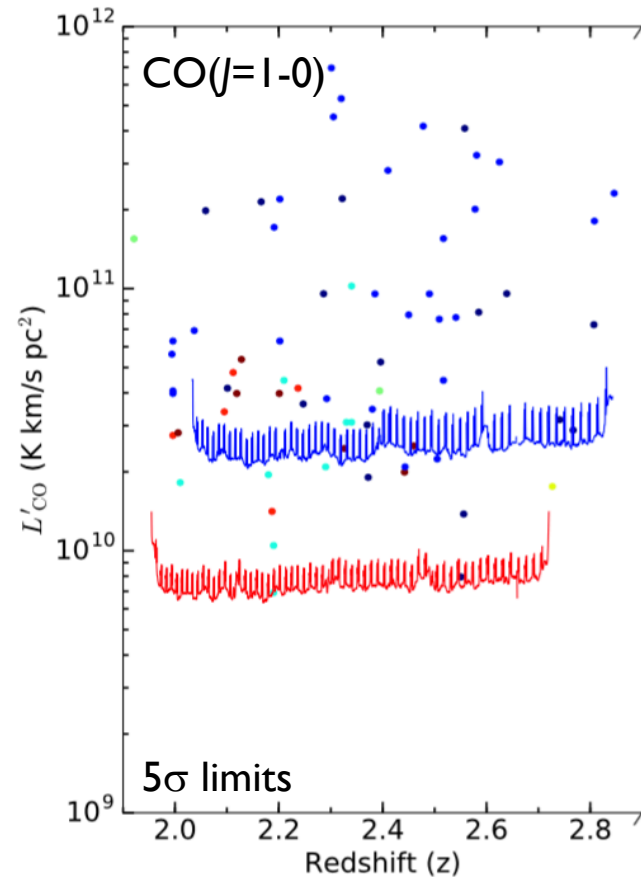
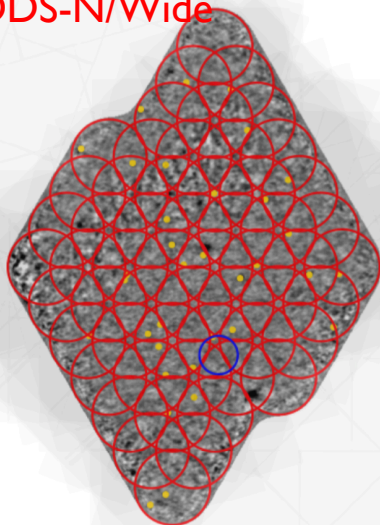
COLDz: Sensitivity

Pavesi, Riechers et al. 2017

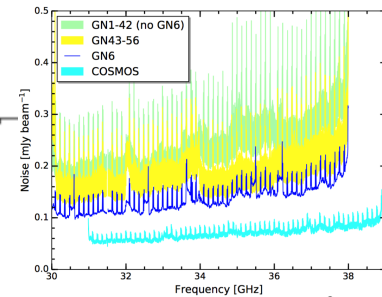
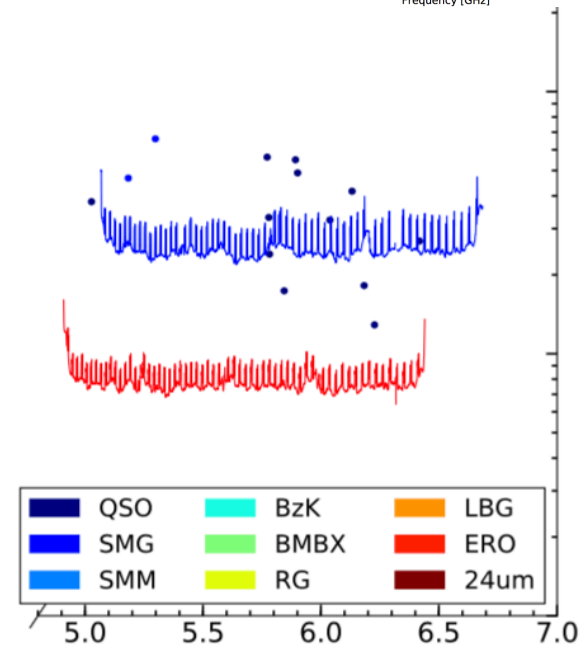
COSMOS/Deep



GOODS-N/Wide

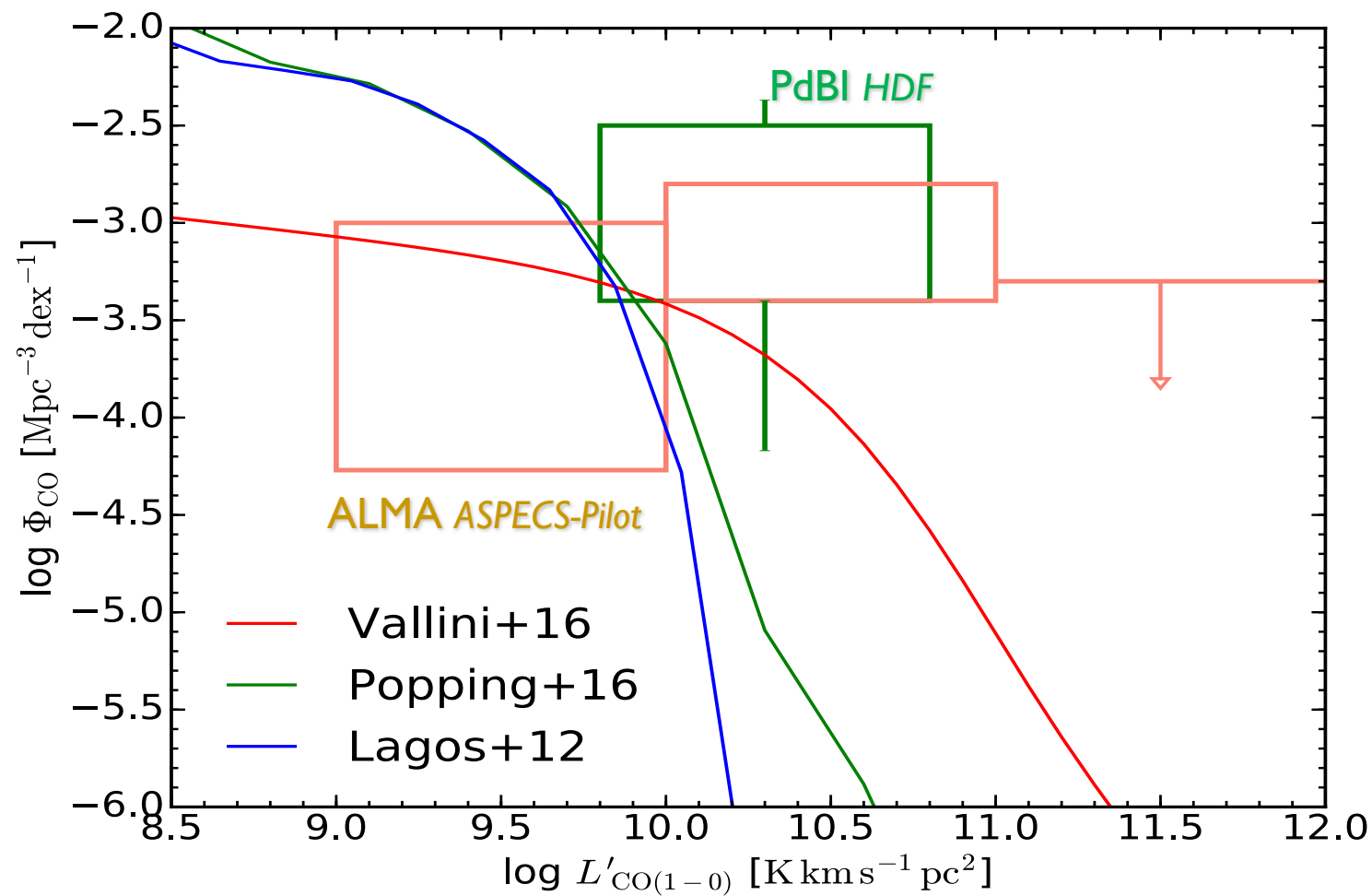


CO(J=2-1)

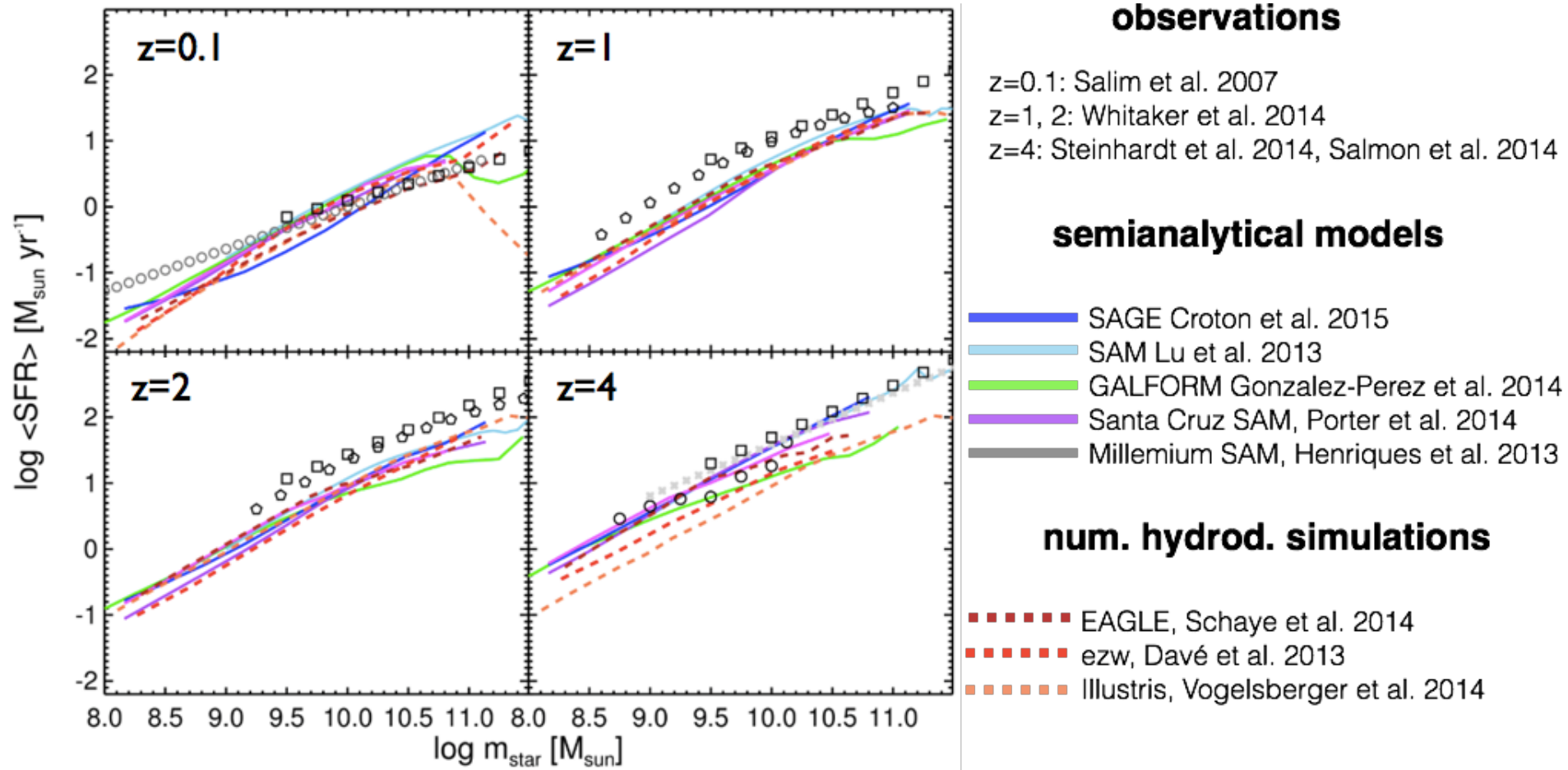


Approx. flat noise across bandpass
 → Resulting in approx. constant CO luminosity limits

Molecular Deep Field: CO Luminosity Function



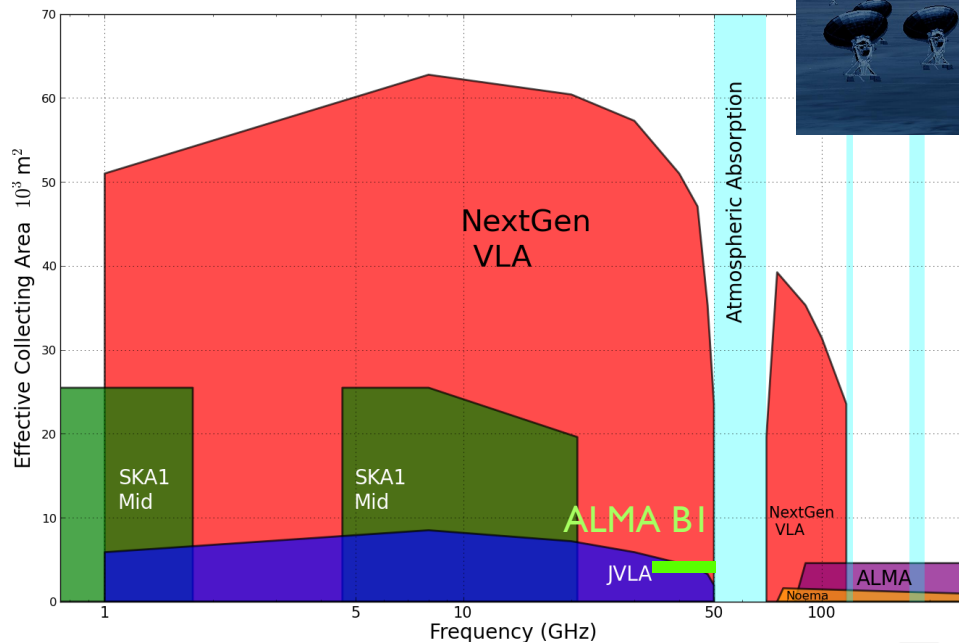
Molecular Deep Field: Comparison to Models/Simulations



All models/simulations **underpredict** SFR in galaxies at $z \sim 1-2$

→ Part of the same problem?

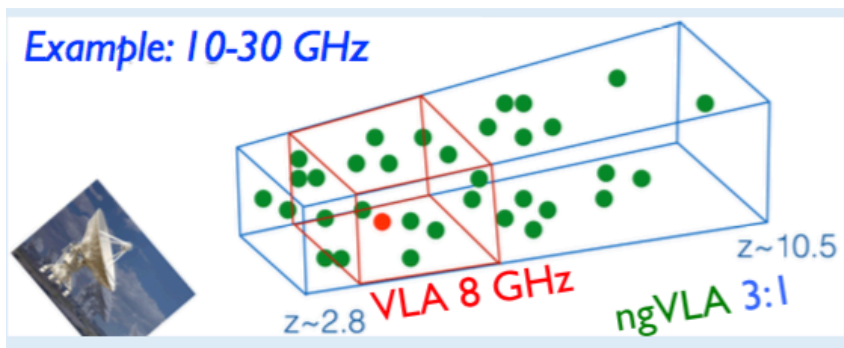
VLA COLDz: Pathfinder for **ngVLA** Science



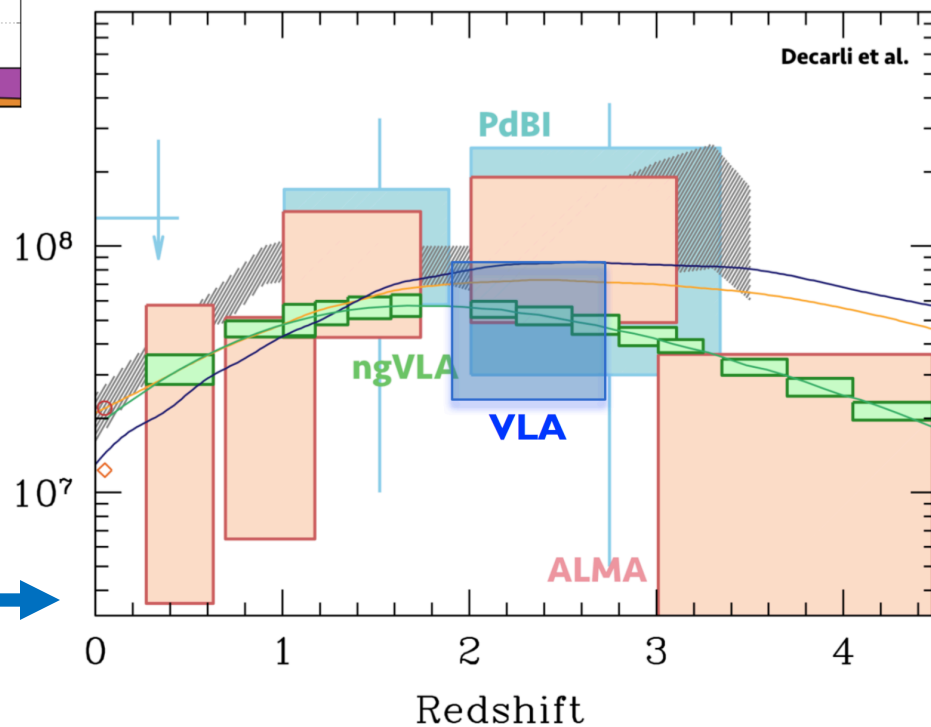
US 2020 Decadal Survey Study:

- 10x eff. resolution & collecting area of VLA
- 1-115 GHz; multiple times VLA bandwidth

→ *The ideal cosmic CO survey machine!*



$\rho(\text{H}_2) [\text{M}_\odot \text{ Mpc}^{-3}]$



- **COLDz**: cosmic H_2 mass density (“cause” of SFR density)
 - needs *direct* molecular gas selection to be unbiased
 - COLDz: VLA directly measures CO($J=1-0$) at $z=2-3$
 - now can measure CO luminosity function out to at least $z\sim 3$
 - high gas fractions at high- z responsible for increase in SFR density
- **COLDz** sources:
 - 54 CO candidates, 7 now confirmed in other CO lines
 - 3 CO($J=2-1$) detections in $z>5$ dusty starburst: high space density!
 - 3.7σ stacked detection of optical spec- z sources: below survey limit
 - To date tightest constraints on CO in “normal” $z>5$ galaxies
- **COLDz** synergies with ngVLA:
 - ngVLA: US Astro 2020 study for next large radio observatory
 - VLA & ALMA deep field surveys are a pathfinder for the ngVLA