



POWER SPECTRUM ANALYSIS OF ASPECS LP BAND 3 DATA: Constraints on CO power from $1 < z < 4$

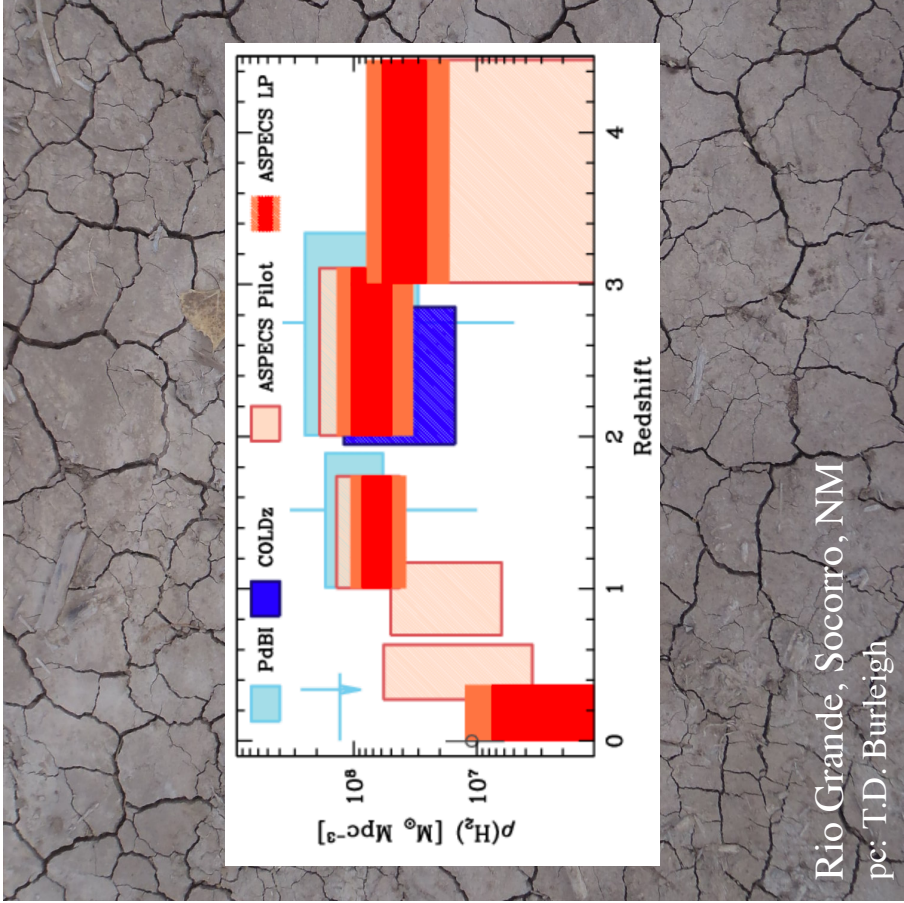


BADE UZGIL



w/ Chris Carilli, Fabian Walter,
Roberto Decarli, Adam Lidz,
Nithya Thyagarajan, & the
ASPECS collaboration

Feb 20, 2019
CCA Workshop on Intensity Mapping



Survey, luminosity functions (LFs),
rho(H2): **Decarli+**, submitted
Line search algorithms in molecular
deep fields: **González-López+**,
submitted



MUSE view of “ASPECS galaxies”:



Boogaard+, submitted



Theoretical implications of the



ASPECS: **Popping+**, submitted



Molecular gas reservoirs in the UDF:



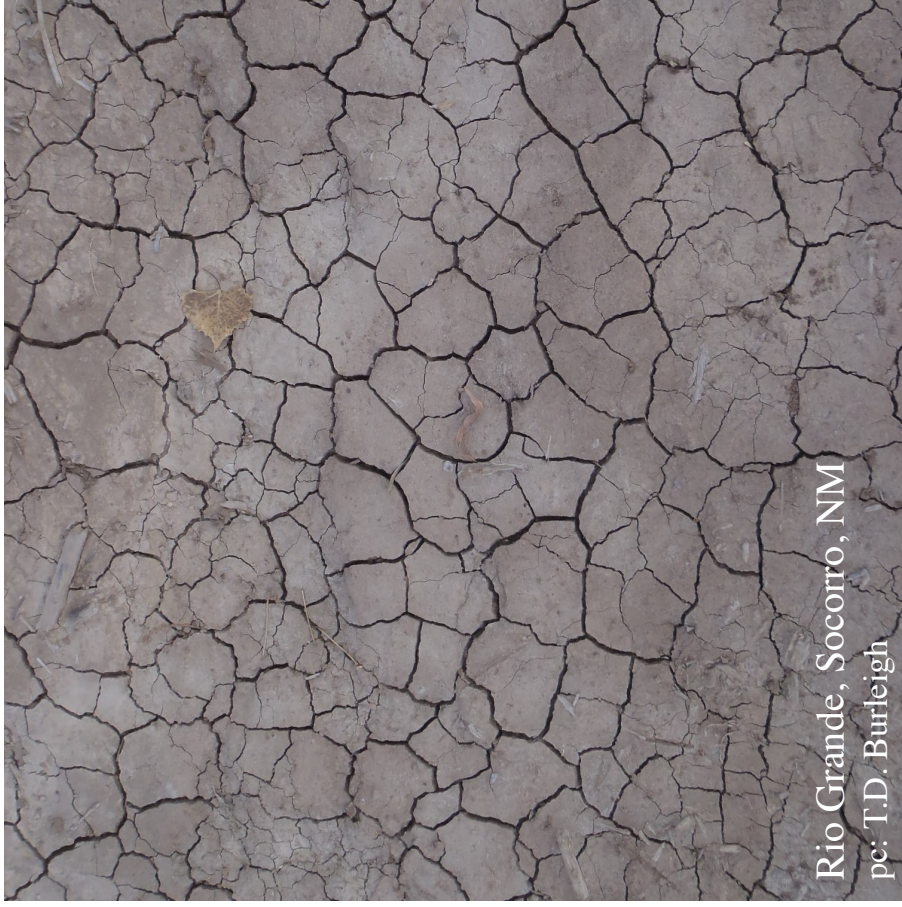
Aravena+in prep



CO search with MUSE spec-z and
pushing CO detections through MUSE
stacking: **Inami+**in prep



Power spectrum: **Uzgil+**in prep



Rio Grande, Socorro, NM
pc: T.D. Burleigh



The auto-power spectrum as a tool to detect emission from galaxies below the survey's sensitivity limit

$$P_{\text{CO,CO}}(k, z) = P_{\text{CO,CO}}^{2\text{h}}(k, z) + P_{\text{CO,CO}}^{1\text{h}}(k, z) + P_{\text{CO,CO}}^{\text{shot}}(k, z) \\ = \left(A \int dL_{\text{CO}} \Phi_{\text{CO}}(L, z) L_{\text{CO}} \right)^2 \langle b_{\text{CO}} \rangle^2 P_{\text{DM,DM}}(k, z) + P_{\text{CO,CO}}^{1\text{h}}(k, z) + A^2 \int dL_{\text{CO}} \Phi_{\text{CO}}(L, z) L_{\text{CO}}^2$$

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1. Constraints on PCO, CO2h from:

- Lower limit on $\langle \text{TCO} \rangle$ from blindly detected CO sources
- Power spectrum measurement at $k < 0.1$ h Mpc⁻¹ compared to models convolved with ASPECS pencil beam WF

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2. Constraints on PCO, COshot from:

- Lower limit from blindly detected CO sources
- Power spectrum measurements at $k > 10$ h Mpc-1 (WF not an issue)

The auto-power spectrum as a tool to detect emission from galaxies below the survey's sensitivity limit

$$P_{\text{CO,CO}}(k, z) = P_{\text{CO,CO}}^{2\text{h}}(k, z) + P_{\text{CO,CO}}^{1\text{h}}(k, z) + P_{\text{CO,CO}}^{\text{shot}}(k, z) \\ = \left(A \int dL_{\text{CO}} \Phi_{\text{CO}}(L, z) L_{\text{CO}} \right)^2 \langle b_{\text{CO}} \rangle^2 P_{\text{DM,DM}}(k, z) + P_{\text{CO,CO}}^{1\text{h}}(k, z) + A^2 \int dL_{\text{CO}} \Phi_{\text{CO}}(L, z) L_{\text{CO}}^2$$

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2. Constraints on PCO, COshot from:

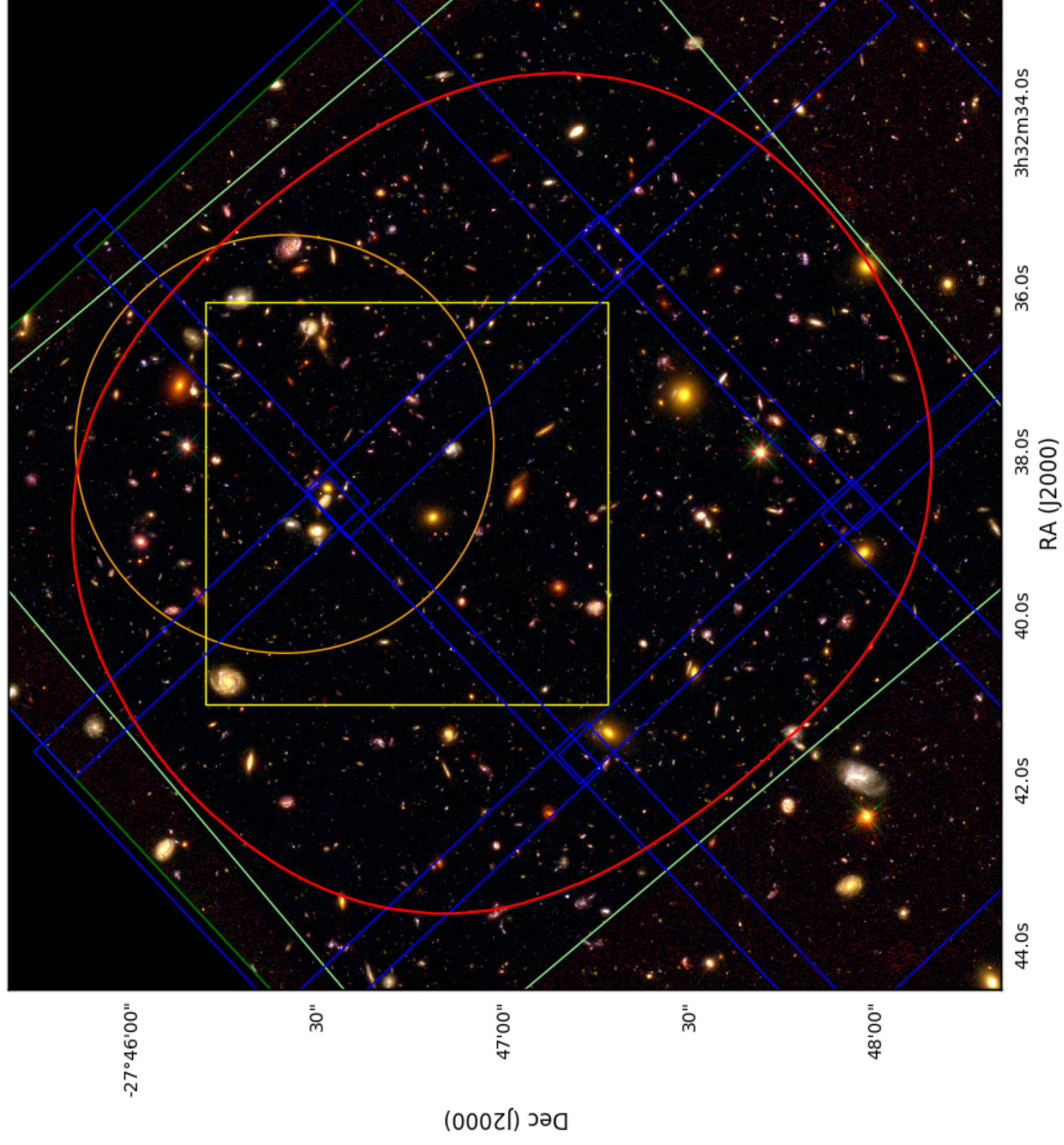
- Lower limit from blindly detected CO sources
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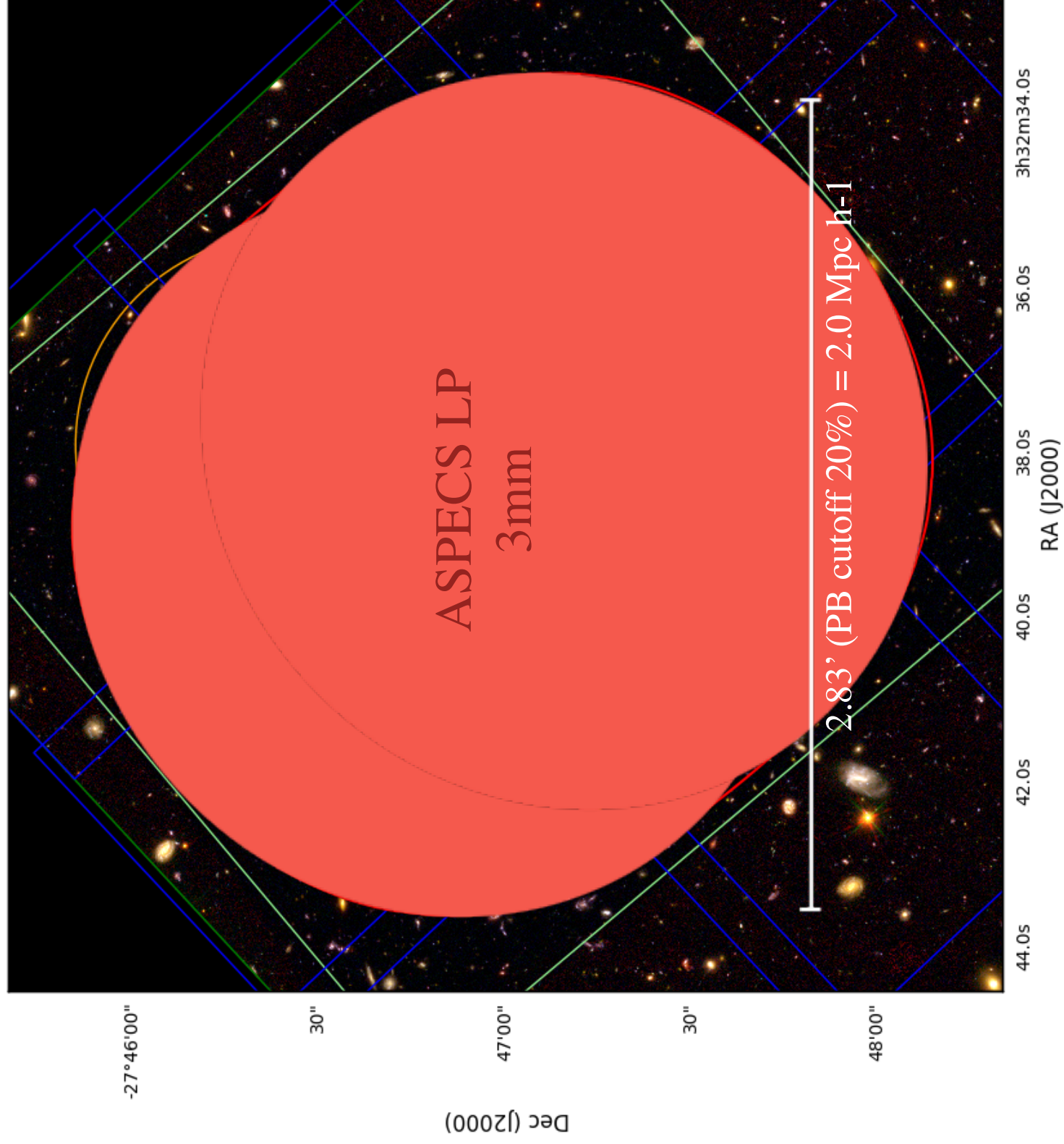
The cross-power spectrum probes correlations between two populations, with (potentially) improved fidelity on the power spectrum measurement

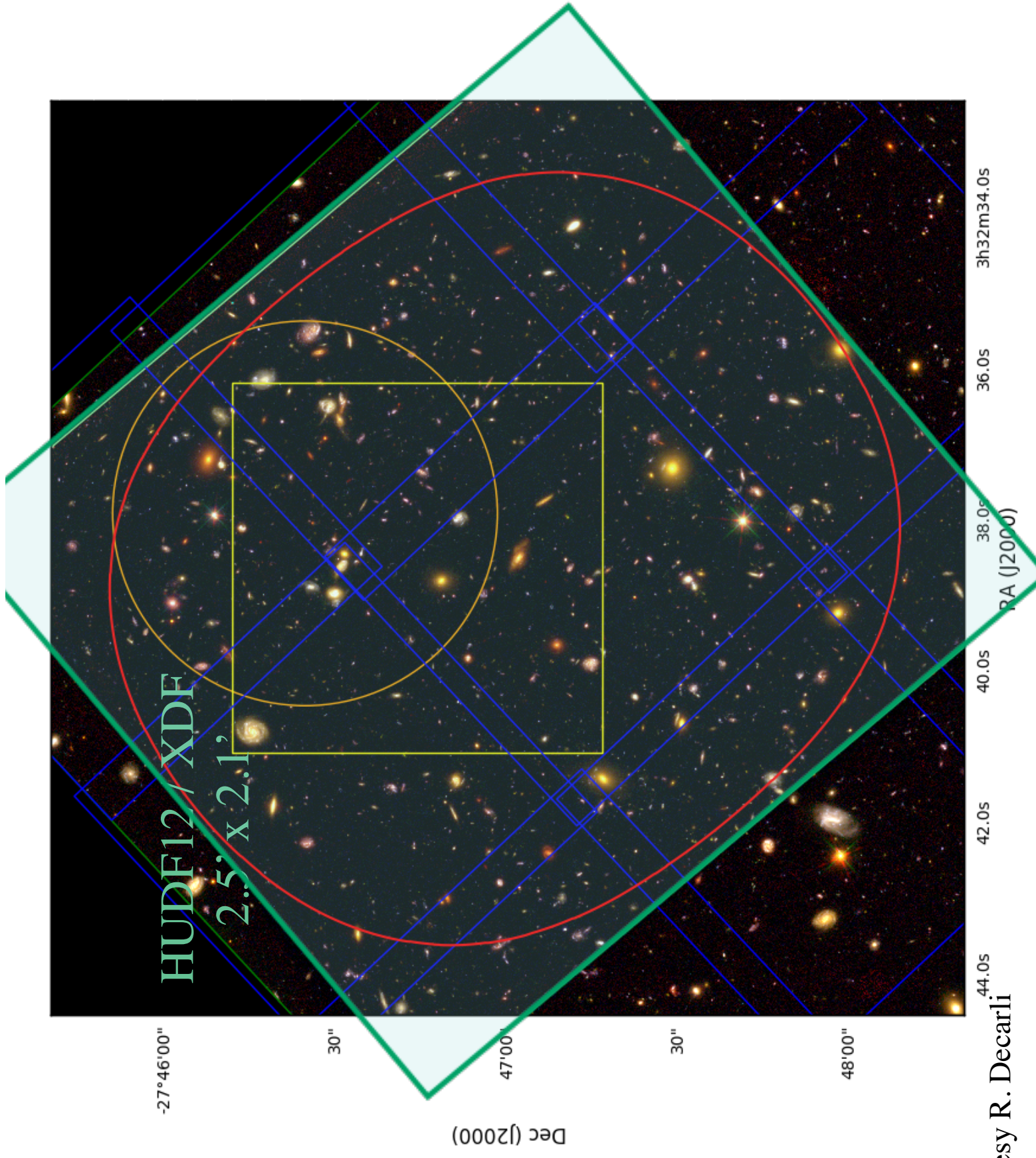
$$P_{\text{CO,gal}}(k, z) = P_{\text{CO,gal}}^{2\text{h}}(k, z) + P_{\text{CO,gal}}^{1\text{h}}(k, z) + P_{\text{CO,gal}}^{\text{shot}}(k, z)$$

3. Constraints on PCO, galshot from:

- Lower limit from blindly detected CO sources
- cross-power spectrum measurements at $k > 10$ h Mpc⁻¹ for the full data cube and a $\sim$ narrow slice across







Courtesy R. Decarli

MUSE-UDS

3' x 3'

Dec (J2000)

-27°46'00"

47'00"

30"

48'00"

Courtesy R. Decarli

~1,500 spectroscopic redshifts

3h32m34.0s

36.0s

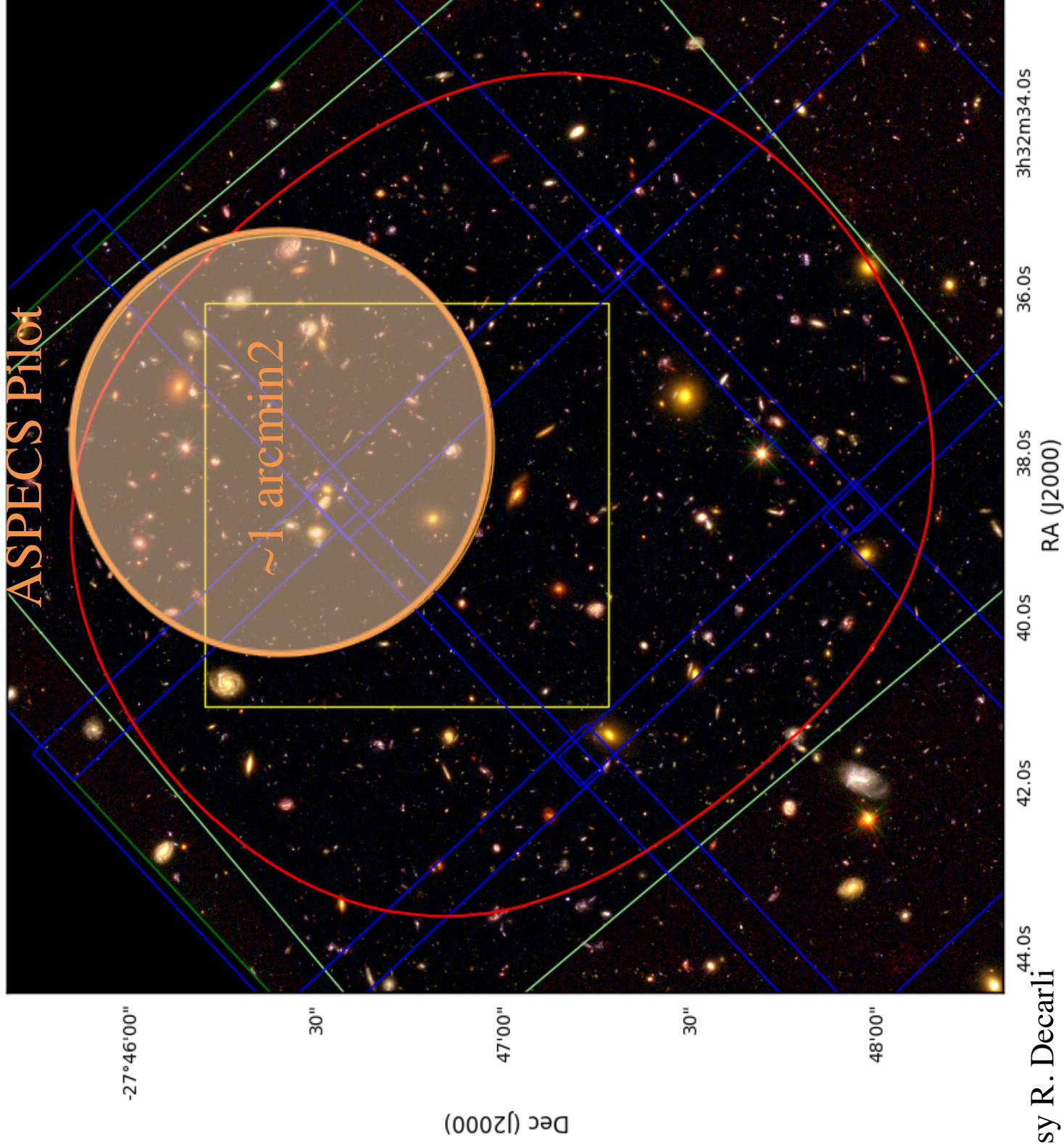
38.0s

40.0s

42.0s

44.0s

RA (J2000)

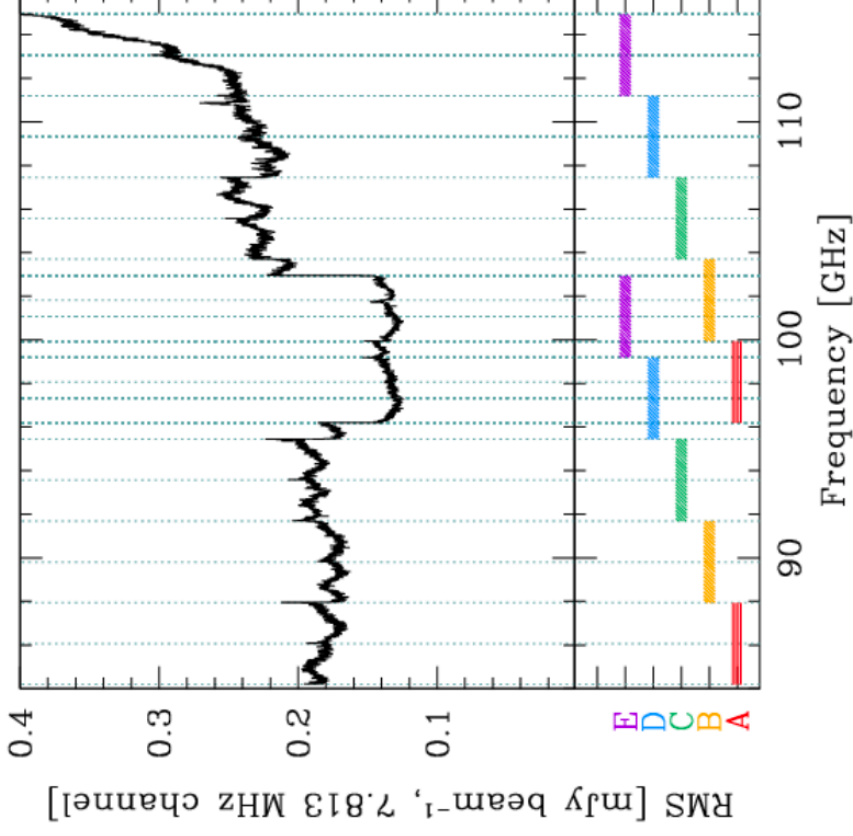


Courtesy R. Decarli

ASPECS survey bandwidth and depth

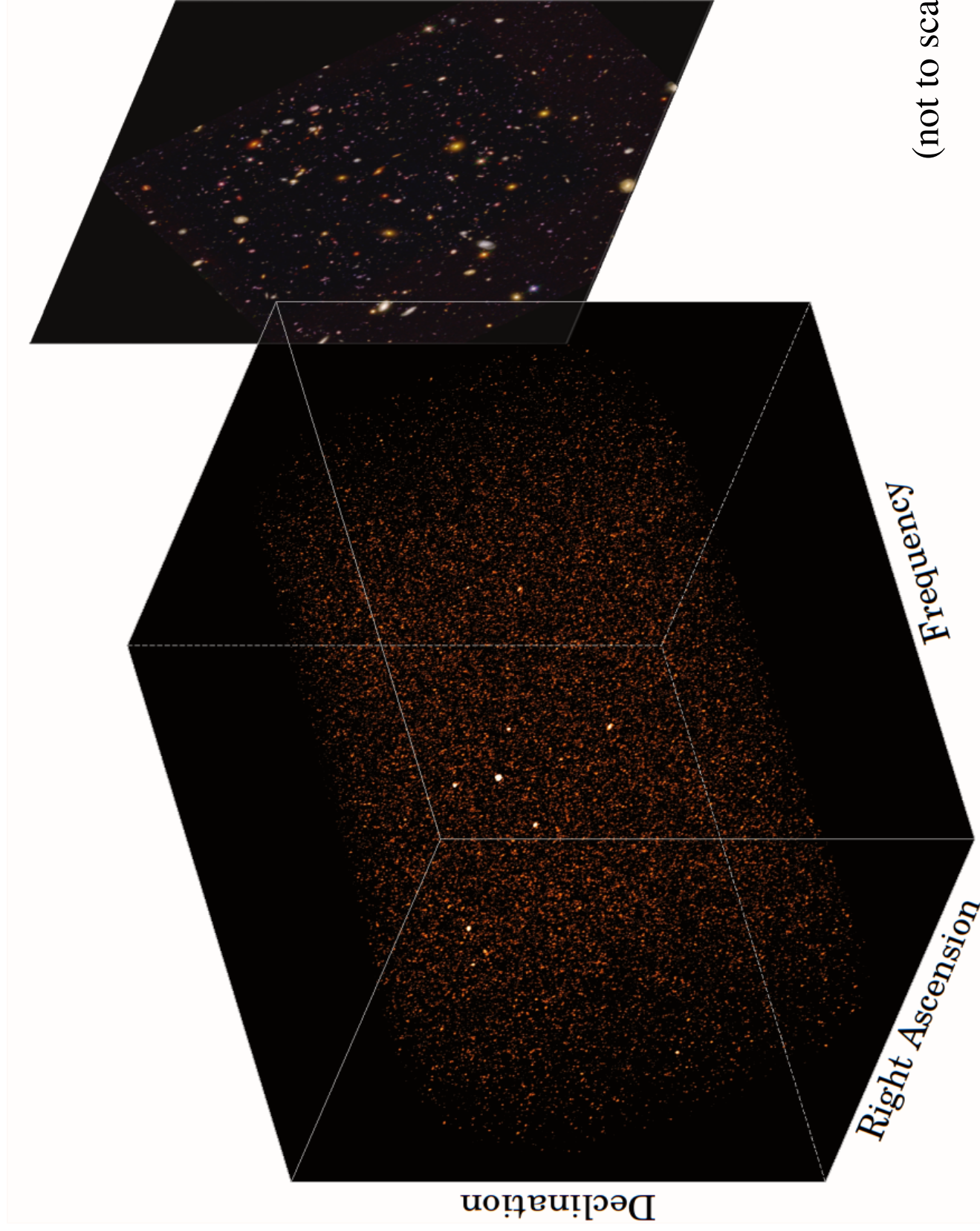
- 68 hours (of ASPECS 150 hour LP) for Band 3 (84-115 GHz) observations
- $\langle \sigma_N \rangle = 0.196$ mJy beam⁻¹ per 7.81 MHz channel (~ 25 km/s at 99 GHz)
- RMS translates to survey depth in H2 mass of $109 M_\odot$ to $\sim 3 \times 1010 M_\odot$ depending on observed CO transition (i.e., redshift)

Decarli+2019

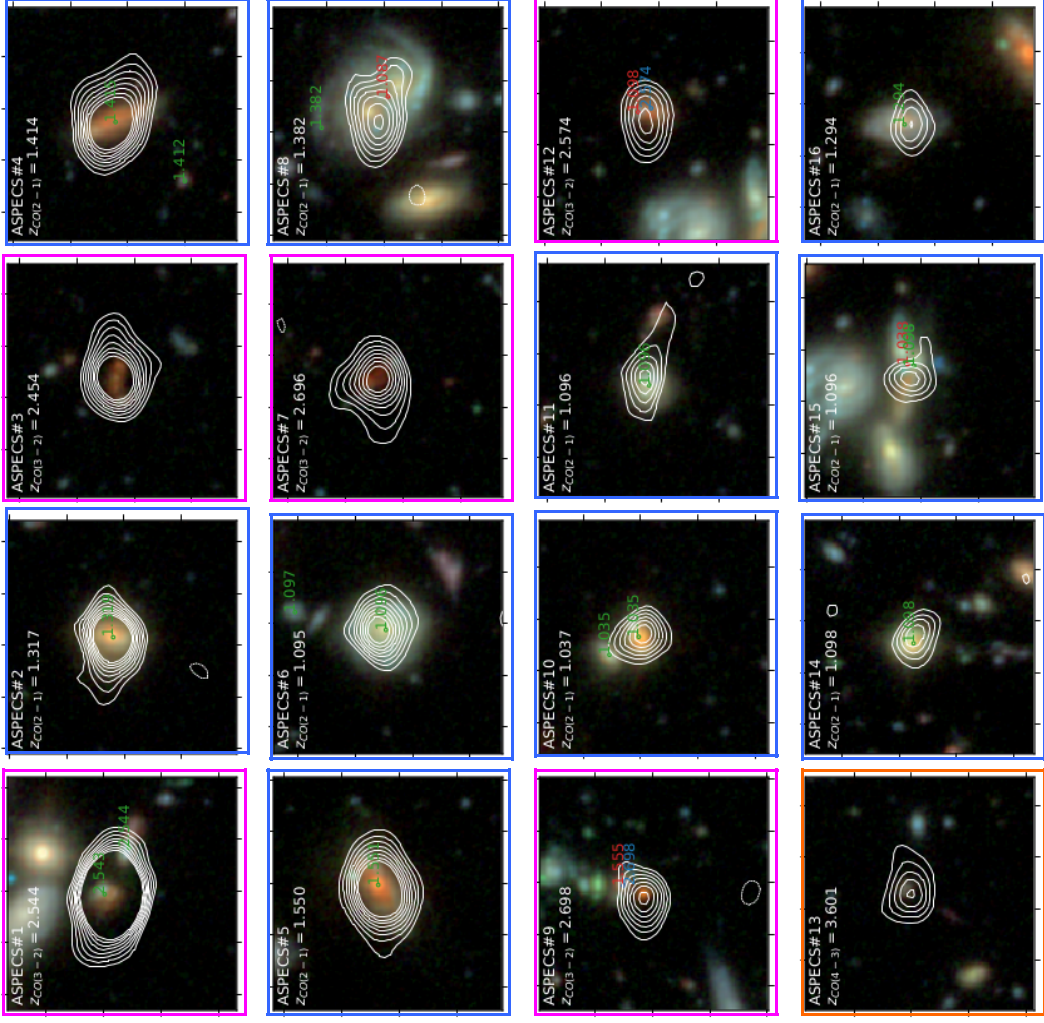


Noise is spectrally and spatially uniform across most of the band/map

ASPECS “SNR” cube



1. Lower limit on $\langle \text{TCO} \rangle$ from blind detections



Boogaard+2019

8''

8''

➤

➤

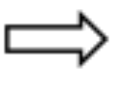
Using line detections from ASPECS-Pilot

$\langle \text{TCO} \rangle_{\text{Pilot}} \geq 0.94 \pm 0.09 \mu\text{K}$

After accounting for spurious sources with improved line search algorithms employed in ASPECS LP,

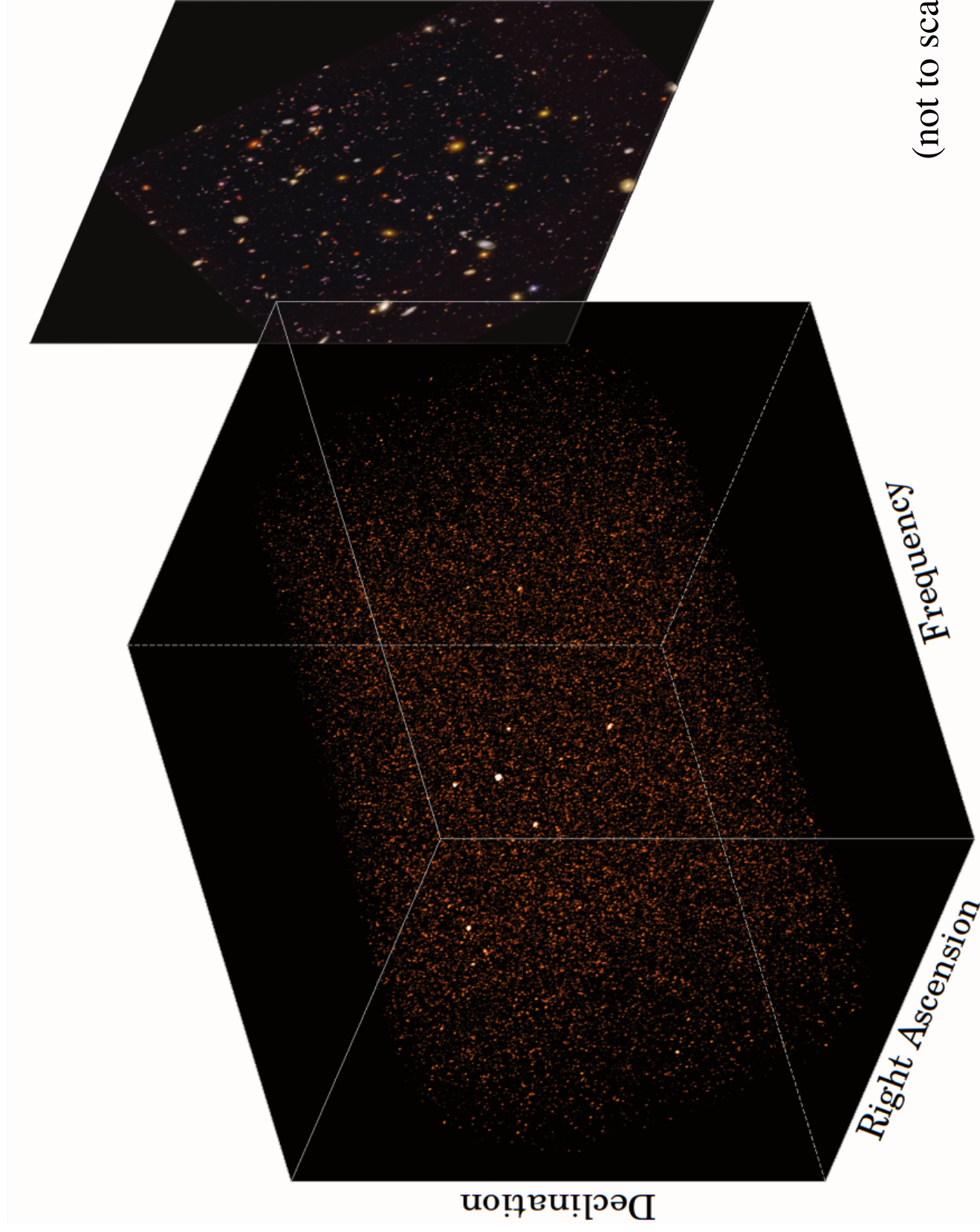
$\langle \text{TCO} \rangle_{\text{Pilot}} \geq 0.55 \pm 0.05 \mu\text{K}$

$\langle \text{TCO} \rangle \geq 0.55 \pm 0.02 \mu\text{K}$



10 CO(2-1) , 5 CO(3-2) , 1 CO(4-3) detections =
 16 total secure blind detections between $1 < z < 4$

ASPECS “SNR” cube



The CO auto-power spectrum measured by ASPECS

$$P_{\text{CO,CO}}(k_{\text{CO}(2-1)}, z_{\text{CO}(2-1)}) = \sum_{J=1}^4 P_{\text{CO}(J-(J-1)), \text{CO}(J-(J-1))}(k_{\text{CO}(2-1)}, z_{\text{CO}(J-(J-1))}) + P_{N,N}(k_{\text{CO}(2-1)})$$

Contains noise term, $P_{N,N}(k) = \sigma_N^2 V_{\text{vox}}$

$\langle \sigma_N^2 \rangle = 0.196$ mJy beam⁻¹ per channel $\rightarrow$ SNR per voxel ~ 0.01

(shot noise regime)

noise term biases power at all k

Remove the noise-bias by taking cross-power spectra of two subsets that are derived from the same dataset in a manner that preserves k -space probed in each subset

Contains contributions from multiple J transitions:

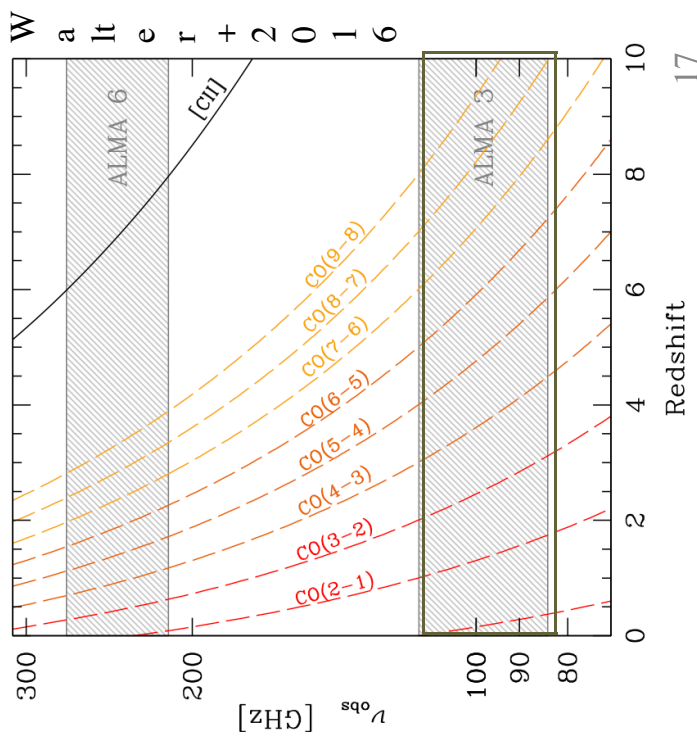
CO(1-0): $0.003 < z < 0.369$

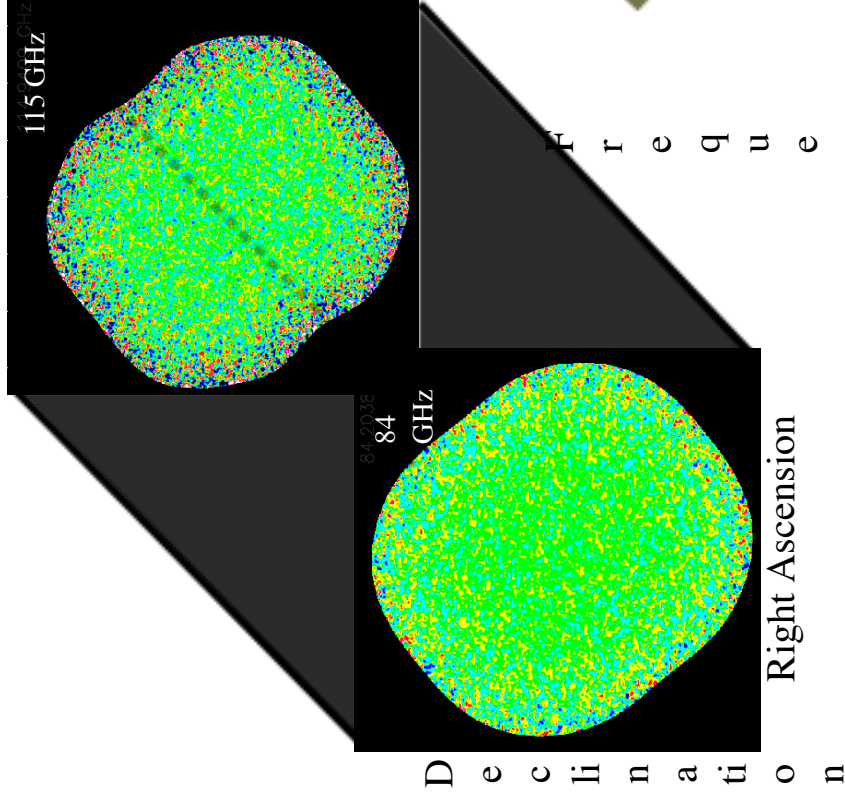
CO(2-1): $1.006 < z < 1.738$

CO(3-2): $2.008 < z < 3.107$

CO(4-3): $3.011 < z < 4.475$

(in principle, higher order J transitions possible, but negligible contributions expected, based on observations)





Real space dimensions:

Channel width (0.155 GHz): 5.38 Mpc/h

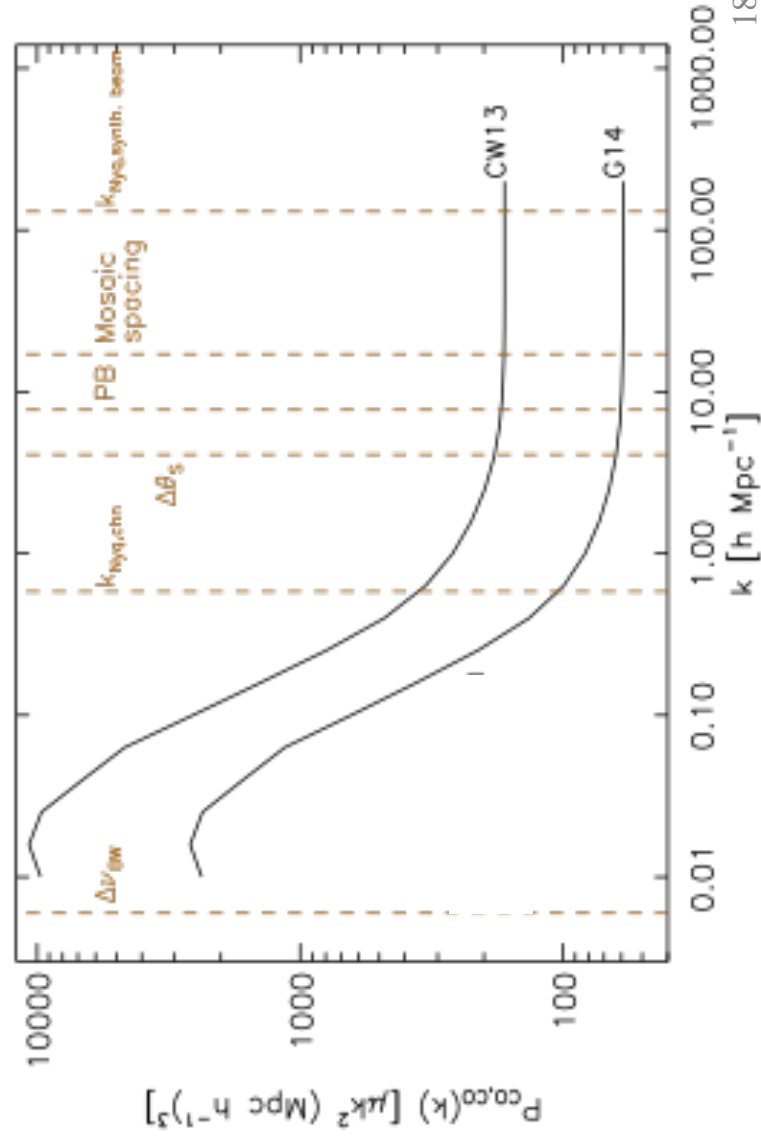
Bandwidth (30 GHz): 1054.8 Mpc/h

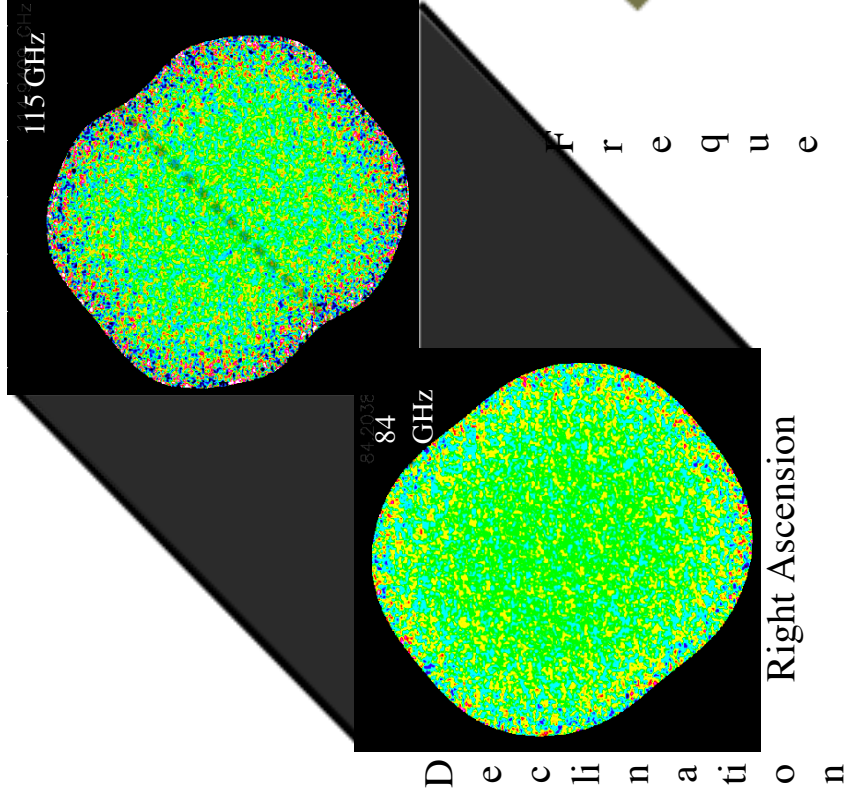
Survey width (1.84'): 1.53 Mpc/h

Synthesized beam(1.8" x 1.5"):
~0.024 Mpc/h

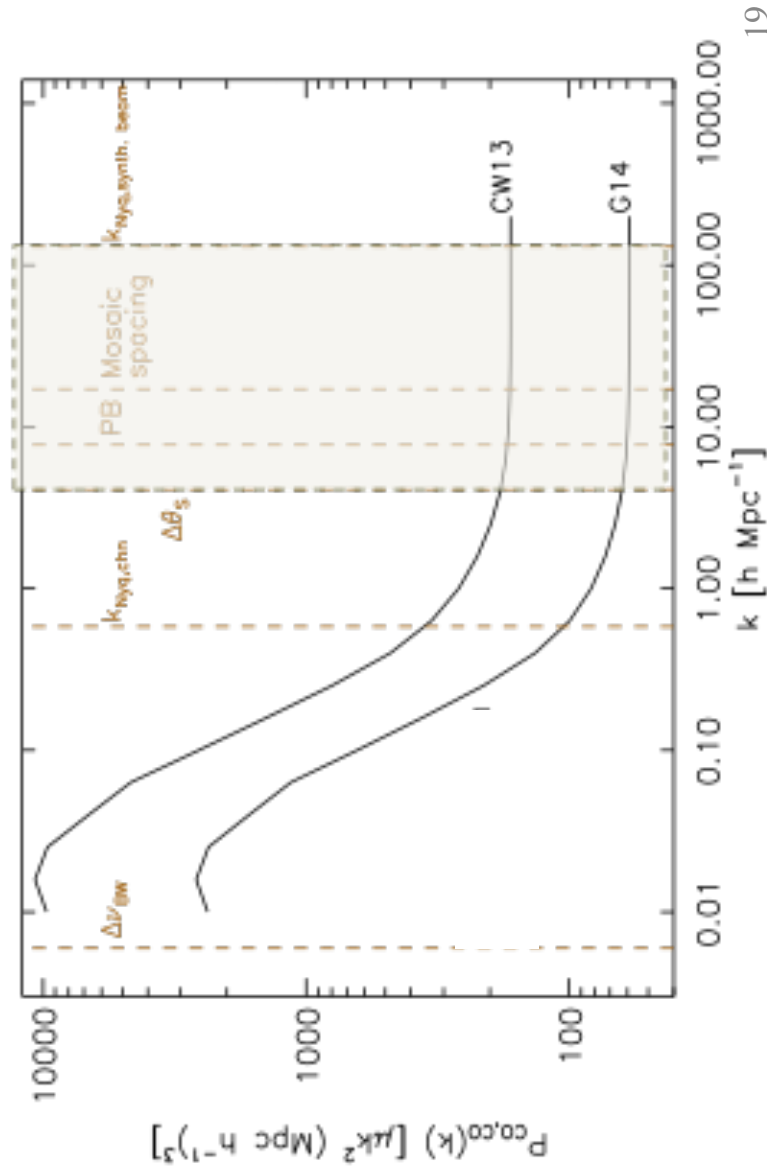
Important k -scales for ASPECS

Adopting redshift $z \sim 1.3$, corresponding to CO(2-1) observed at bandcenter (99.5 GHz)





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Real space dimensions:

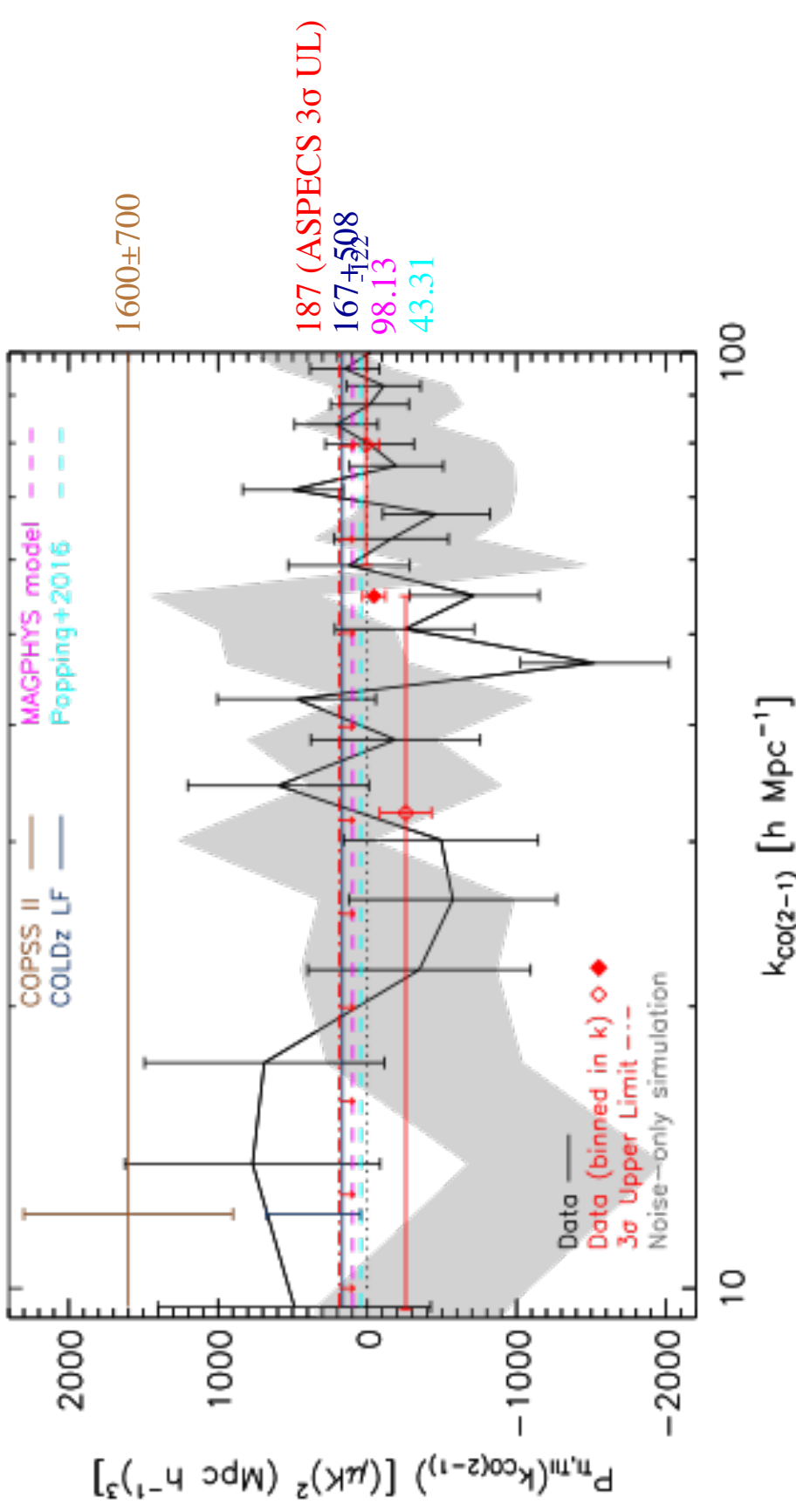
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Survey width (1.84'): 1.53 Mpc/h

Synthesized beam(1.8" x 1.5"):
~0.024 Mpc/h

2. Constraints on PCO, COshot: noise-bias free CO auto-power spectrum



➤ Power in each k bin is consistent with:

- zero ➔ $\text{PCO, CO} \leq 187.29 \mu\text{k}^2 (\text{Mpc } h^{-1})^3$ (3 σ UL)

- simulated noise

- all k bins ➔ no discernable spectral structure

➤ Theoretical models lie below our upper limit by factors of 2 to 4.5

➤ Lower limit from detected sources: $113.24 \mu\text{k}^2 (\text{Mpc } h^{-1})^3$

➤ COPSS II and COLDz LFs provide independent and inconsistent constraints on CO(1-0) power at $z \sim 2.5-2.8$:

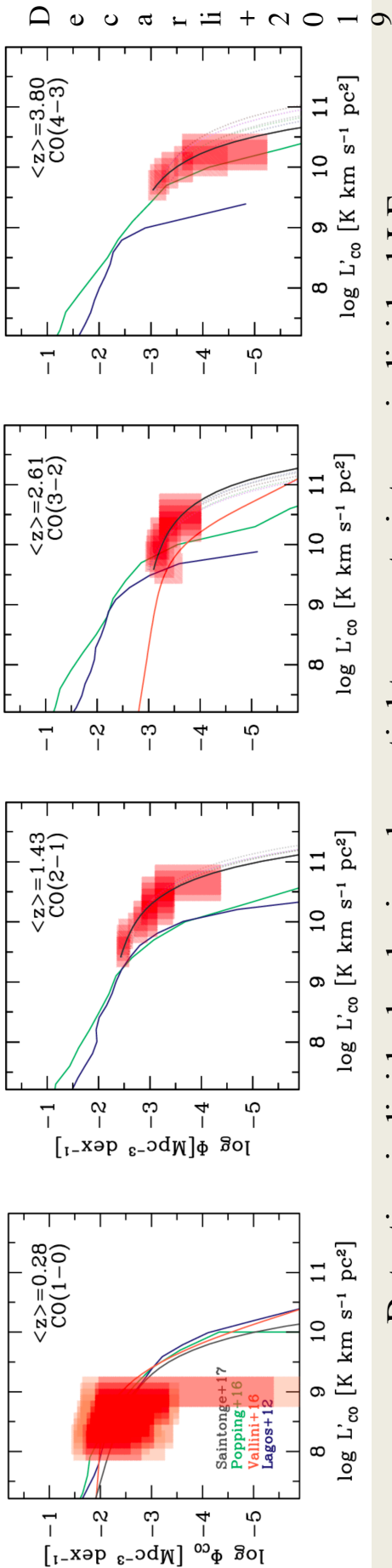
- Extrapolate their observations to estimate CO(2-1) power at $z \sim 1$:

- COLDz consistent w/ 3 σ UL

- COPSS II $\sim 5-12\times$ greater than 3 σ UL

Comparison to CO luminosity functions (LFs) measured by ASPECS

- LF analysis includes ~600 additional CO line candidates at lower SNR
- Sample probes fainter luminosities than the 16 high-fidelity blind detections, using Monte Carlo approach to account for fidelity of lines, uncertainties in line identification, etc.



Detecting individual galaxies places tighter constraints on individual LFs

Line	Popping et al. 2016	MAGPHYS model	ASPECS LF	COLDz LF	COPS II
(1)	(2)	(3)	(4)	(5)	(6)
CO(1-0)	0.55	0.035	0.04 ^{+0.31} _{-0.03}	–	–
CO(2-1)	8.15	89.23	160.34 ^{+155.43} _{-147.15}	167.03 ^{+508.95} _{-121.89}	1600 ± 700
CO(3-2)	17.82	8.61	175.69 ^{+531.35} _{-107.82}	–	–
CO(4-3)	8.77	6.33	27.67 ^{+58.73} _{-18.36}	–	–
Total ^a	43.31	98.13	269.20 ^{+473.51} _{-214.53}	–	–

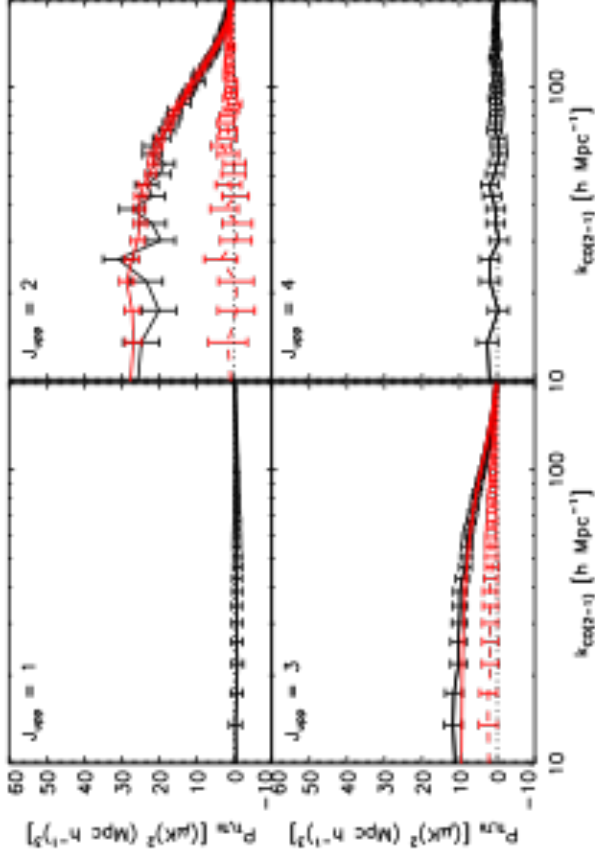
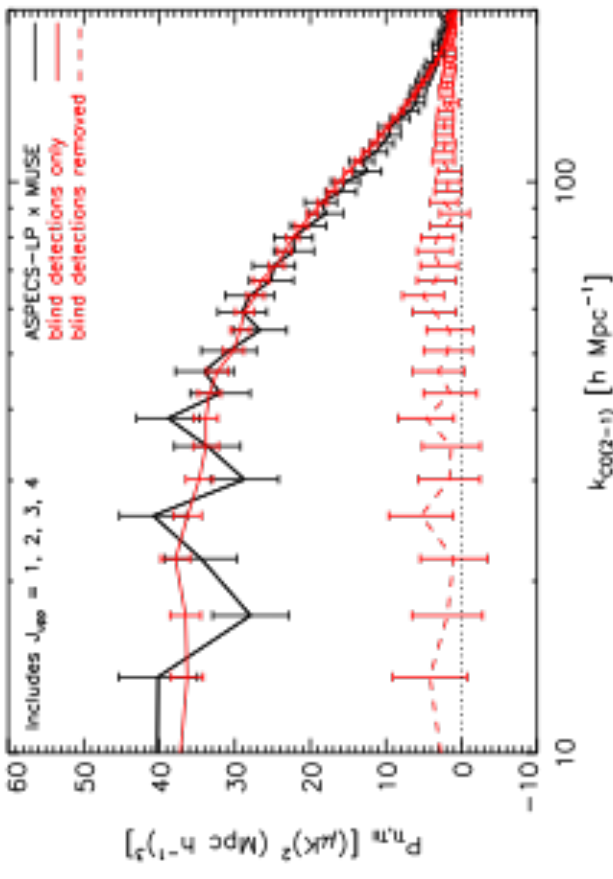
Power spectrum places tighter constraints on the *total* CO power than the LFs due to large uncertainties in Schechter parameters (particularly CO(3-2))

- For Schechter form LFs, PCO,COshot, suggests lower L* or Φ* (less likely) at high-z for fixed $\alpha = -0.21$
- For fixed lower L* or Φ* , α cannot be steeper than -1.0 for all z

3. Detection of PCO_{gal}shot: noise-bias free CO-galaxy cross power spectrum

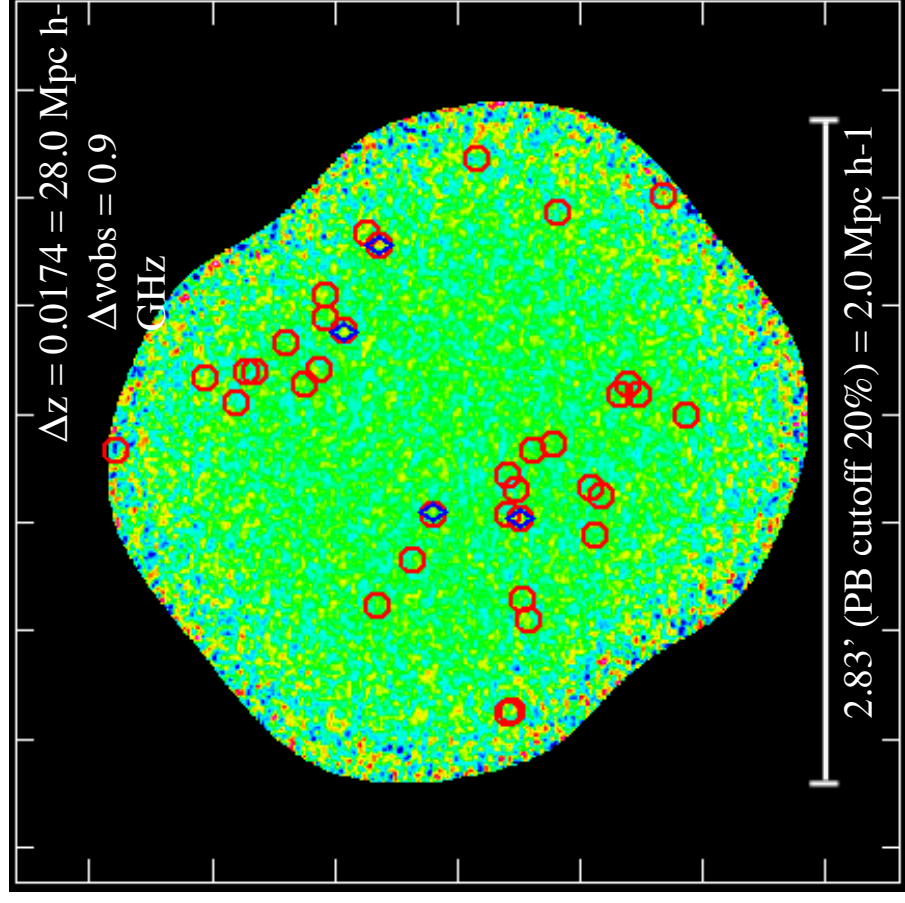
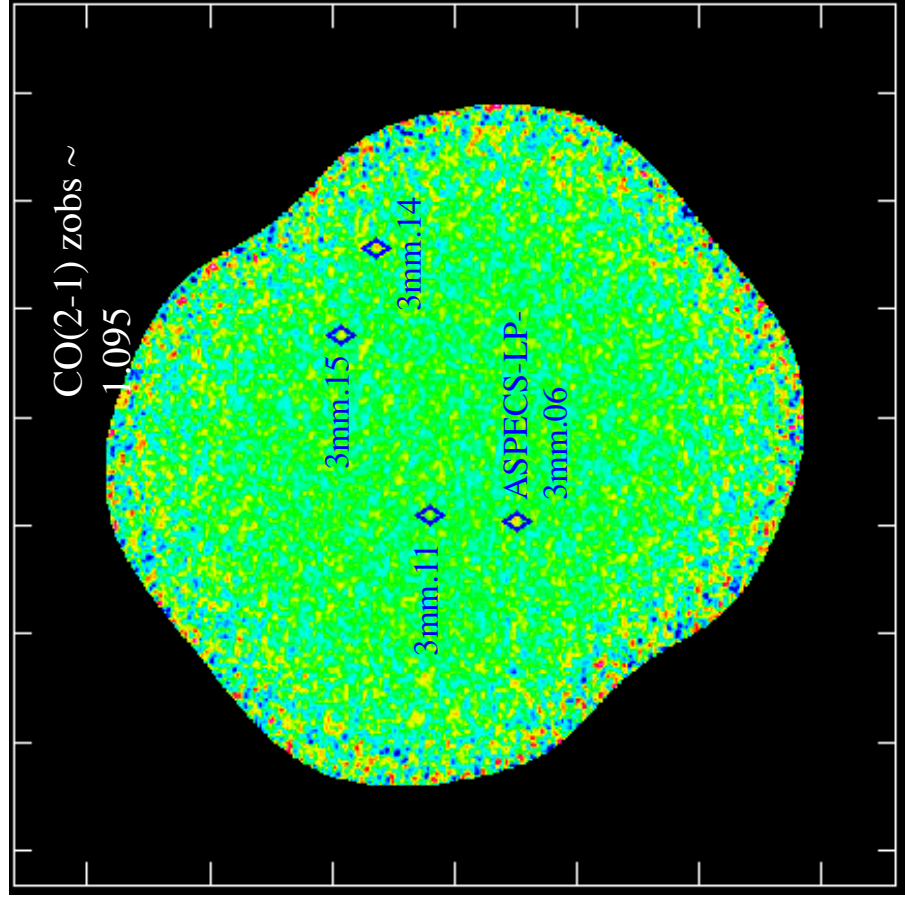
Remove noise-only modes via the cross-power spectrum

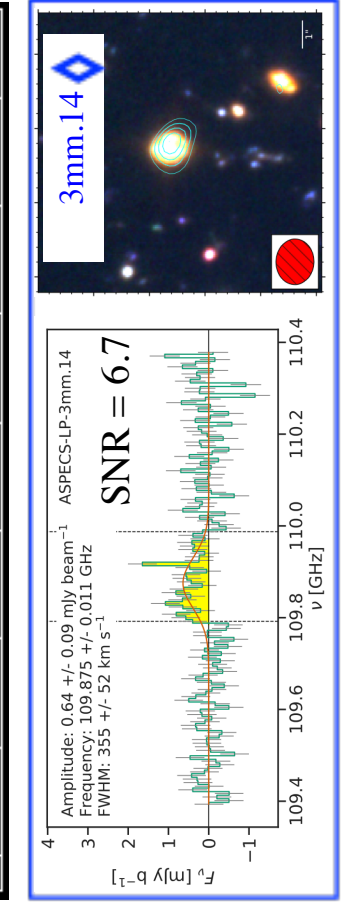
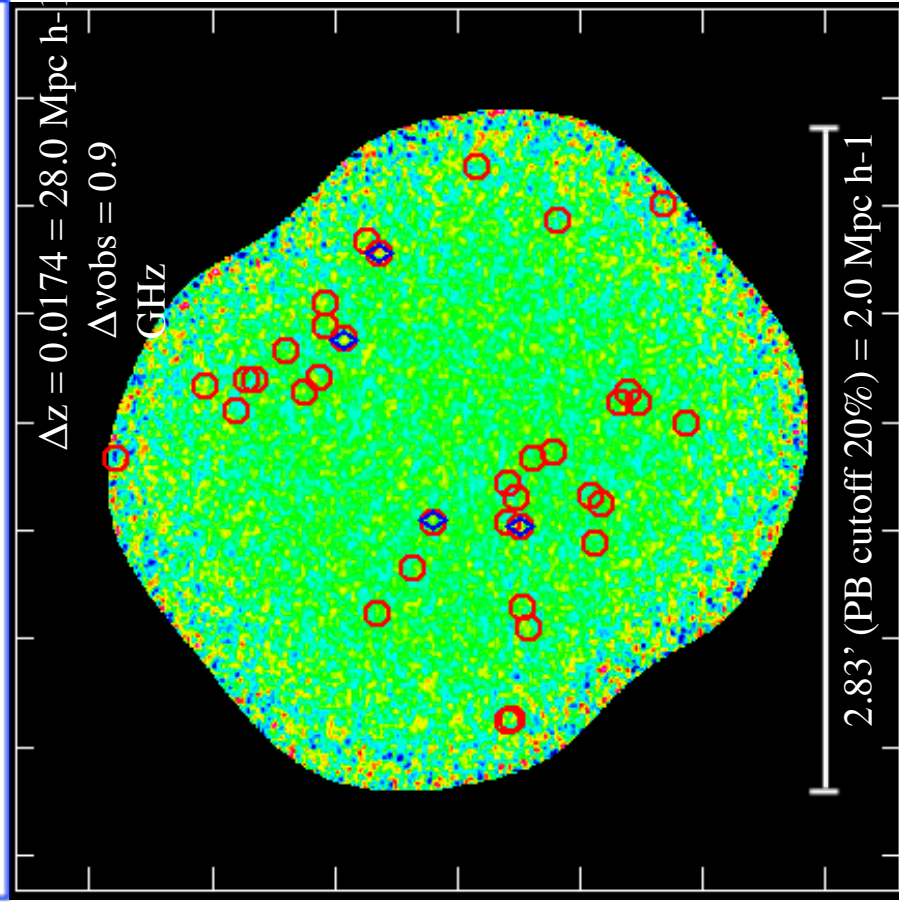
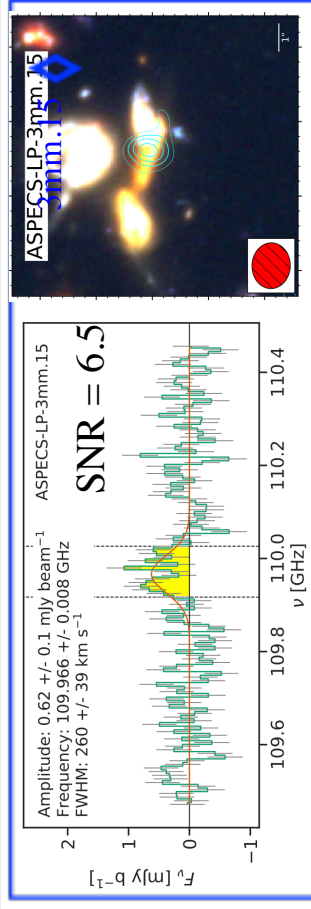
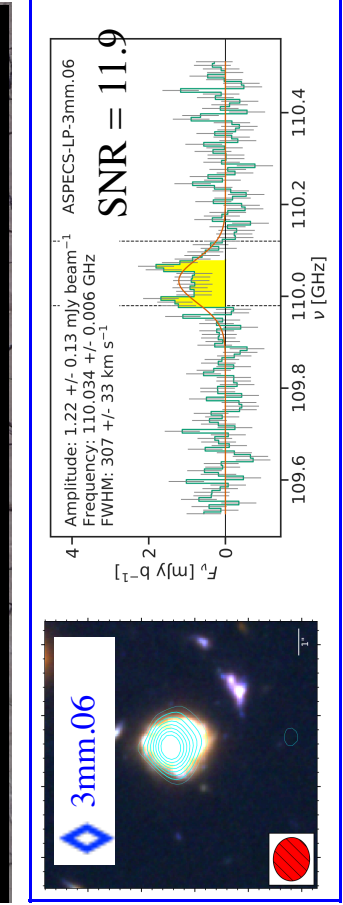
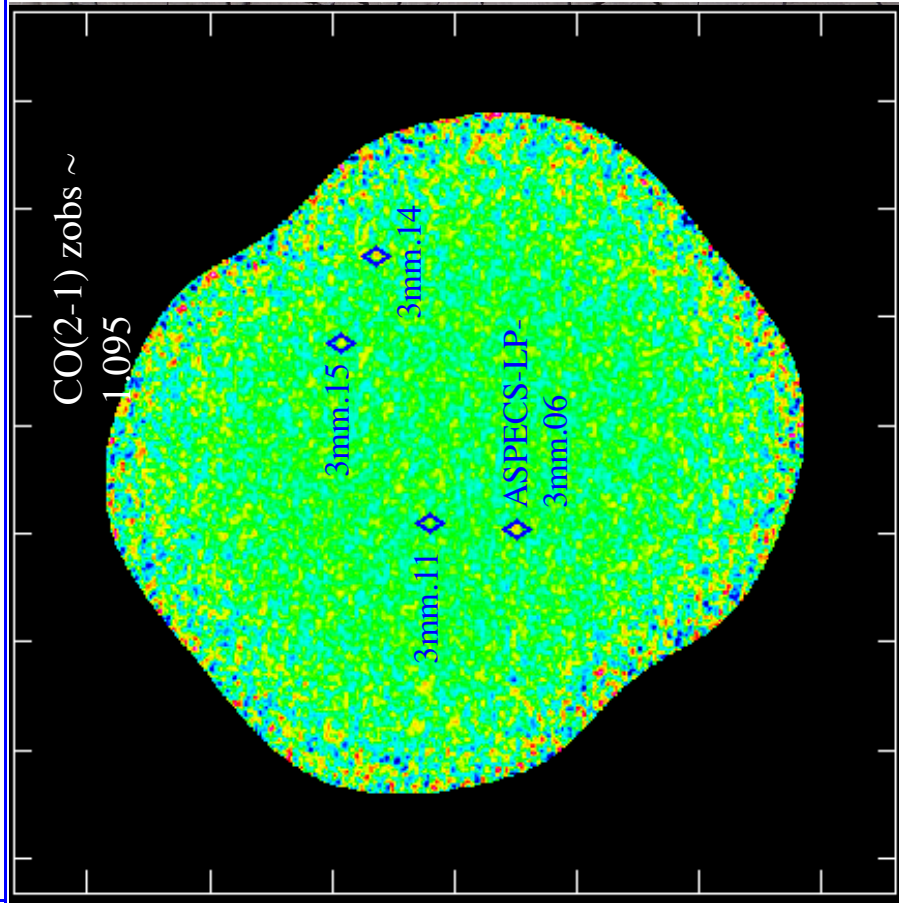
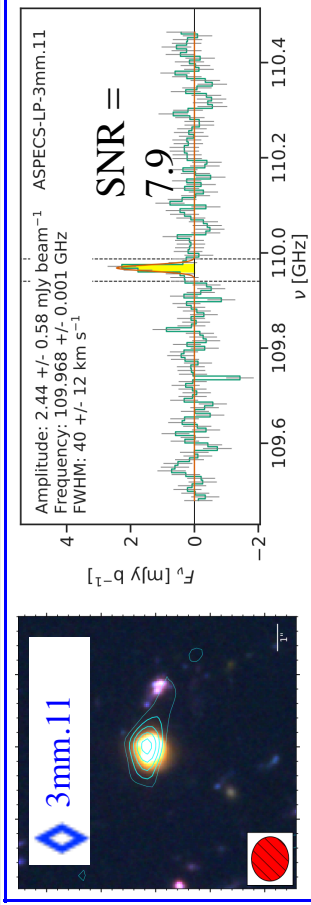
- 680 MUSE spec-z's available for cross-power spectrum
- CO-MUSE cross-power spectrum detected at high significance ($\sim 30\sigma$)
- Rest-frame optical/UV galaxies trace the observed CO emission very closely
- ASPECS blind detections account for $>90\%$ of the cross-power



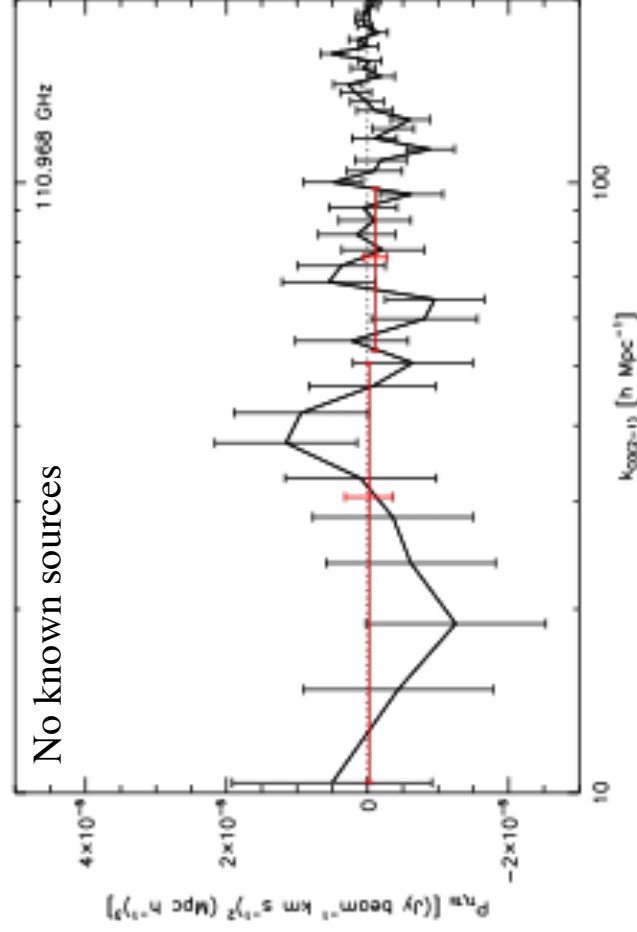
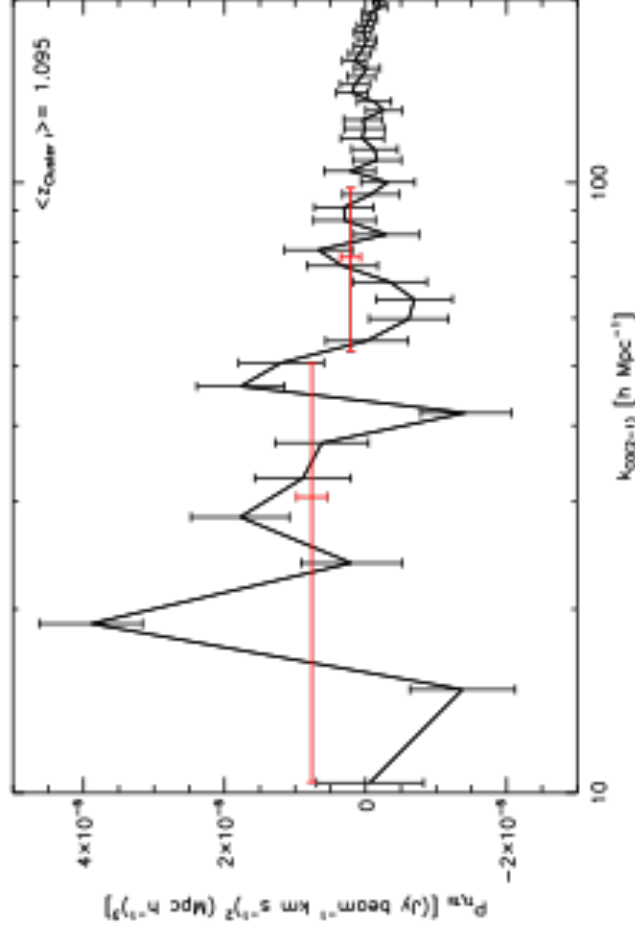
- Small excess power observed from MUSE galaxies without previously detected ASPECS counterpart
- Use high SNRs on the cross-power to identify the source of the excess as MUSE galaxies with CO(3-2) emission at $z \sim 2.5$
- Masking analysis reveals source of emission as likely one or two galaxies just below L_{min}, but similar in luminosity to CO-emitters identified with MUSE spec-z prior (and missed by the blind search)

2-dimensional power spectra of previously known CO associations



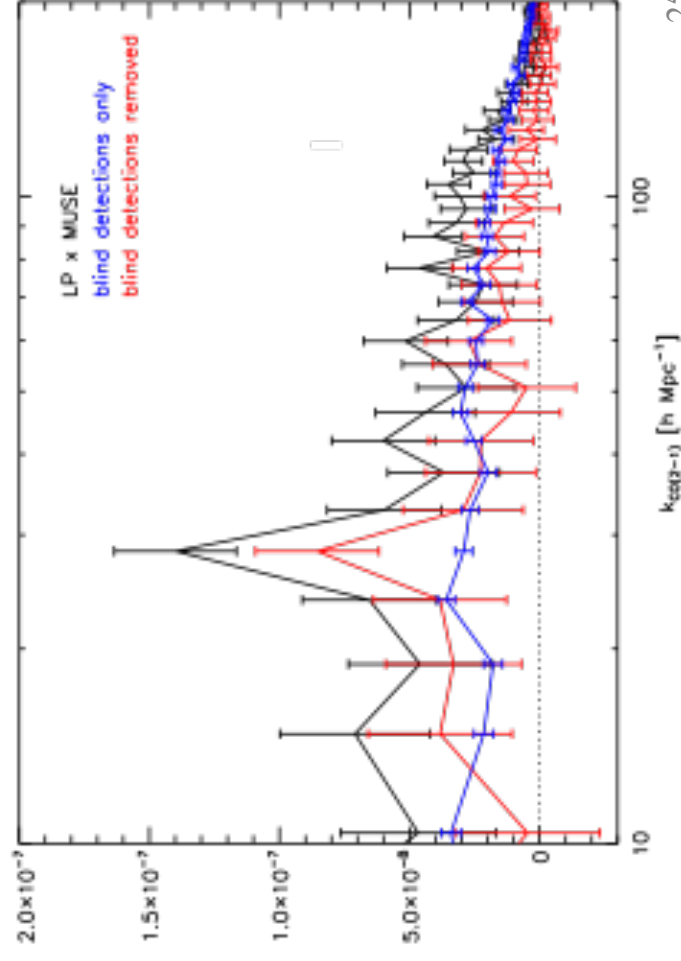


Noise-bias free autopower



- CO auto-power detected at $\sim 3.5\sigma$
- Auto-power consistent with zero in neighboring channels without known sources
- ASPECS blind detections only account for $\sim 50\%$ of observed CO-MUSE cross-power

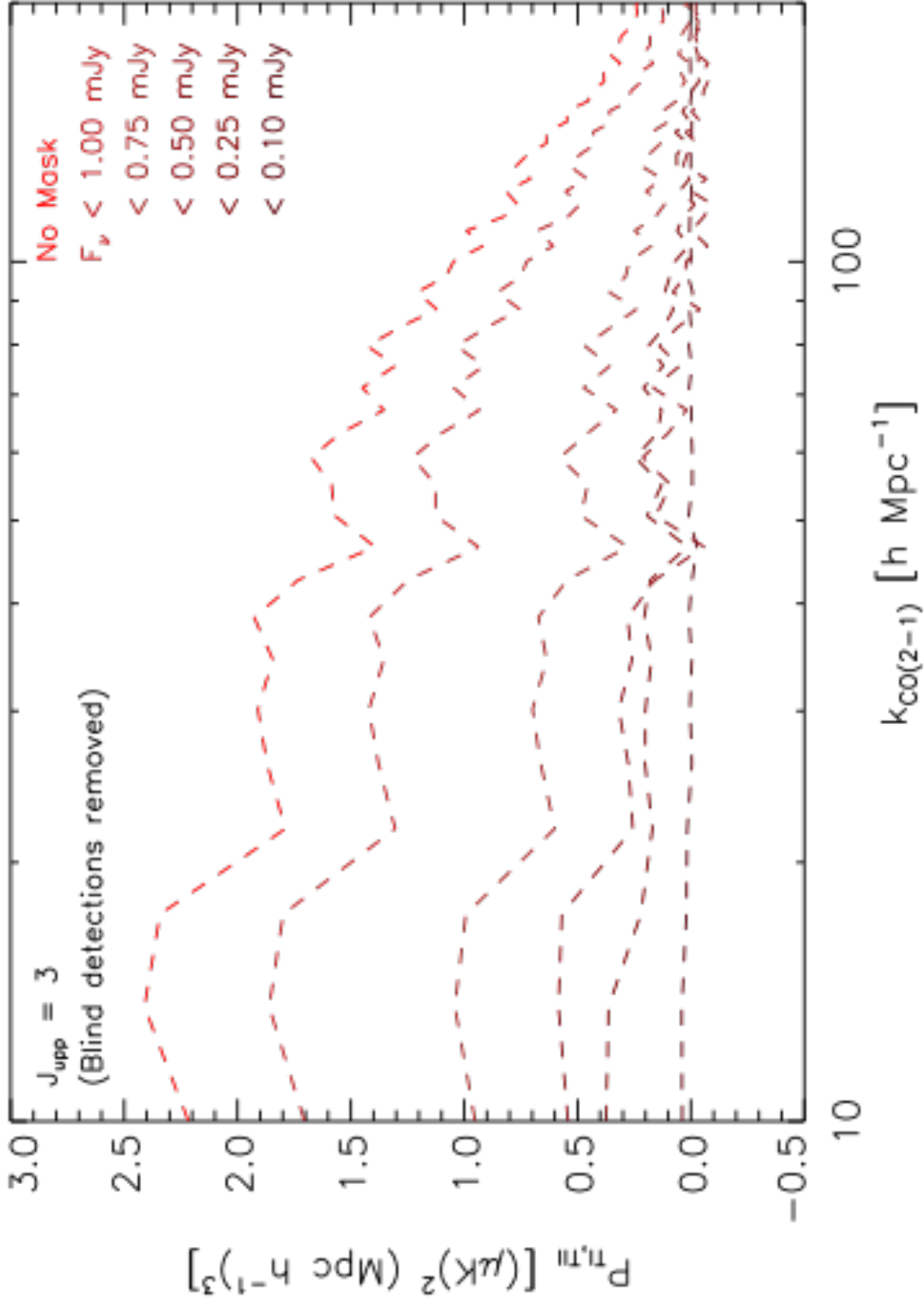
Noise-bias free CO-MUSE cross-power

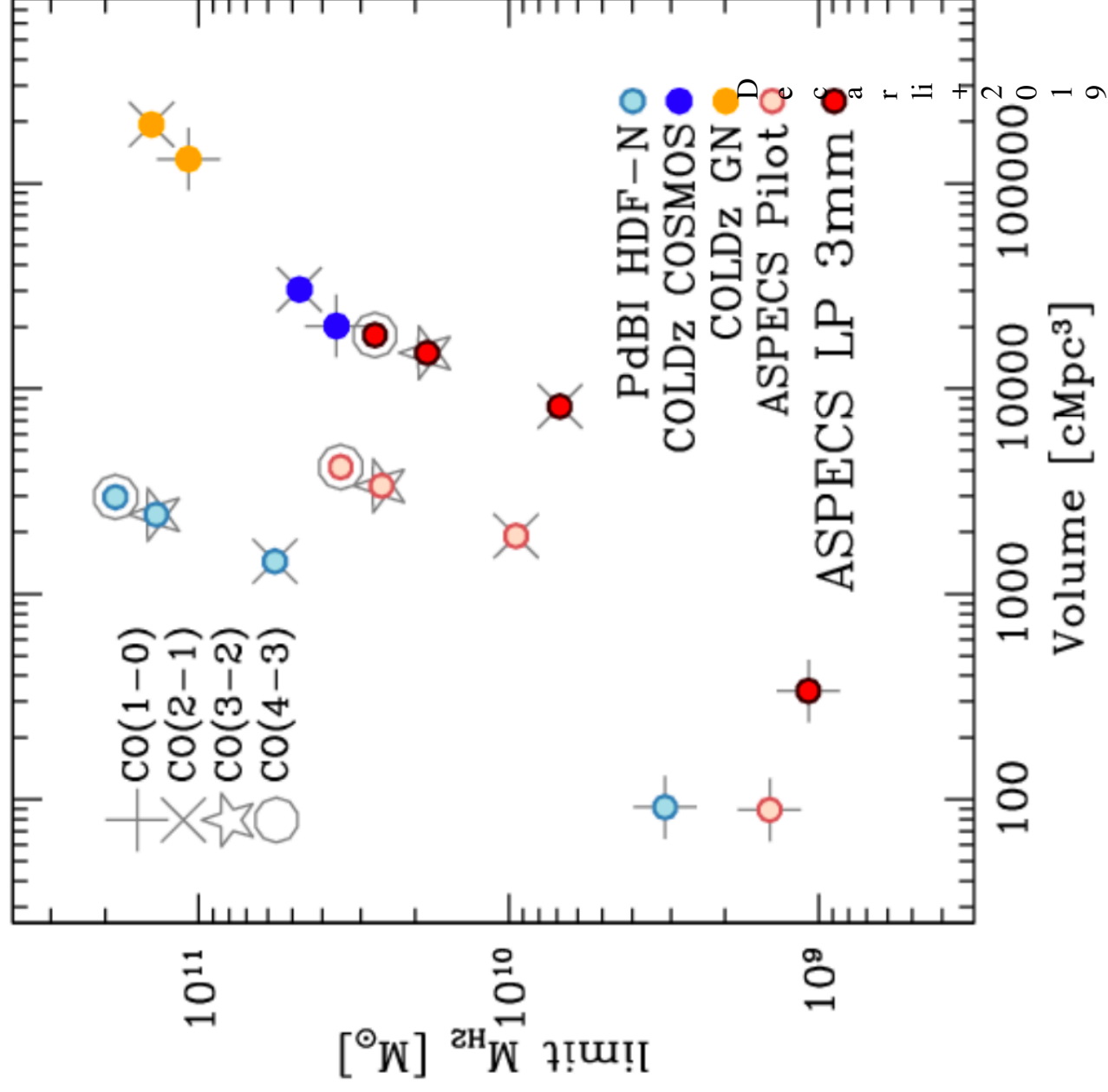


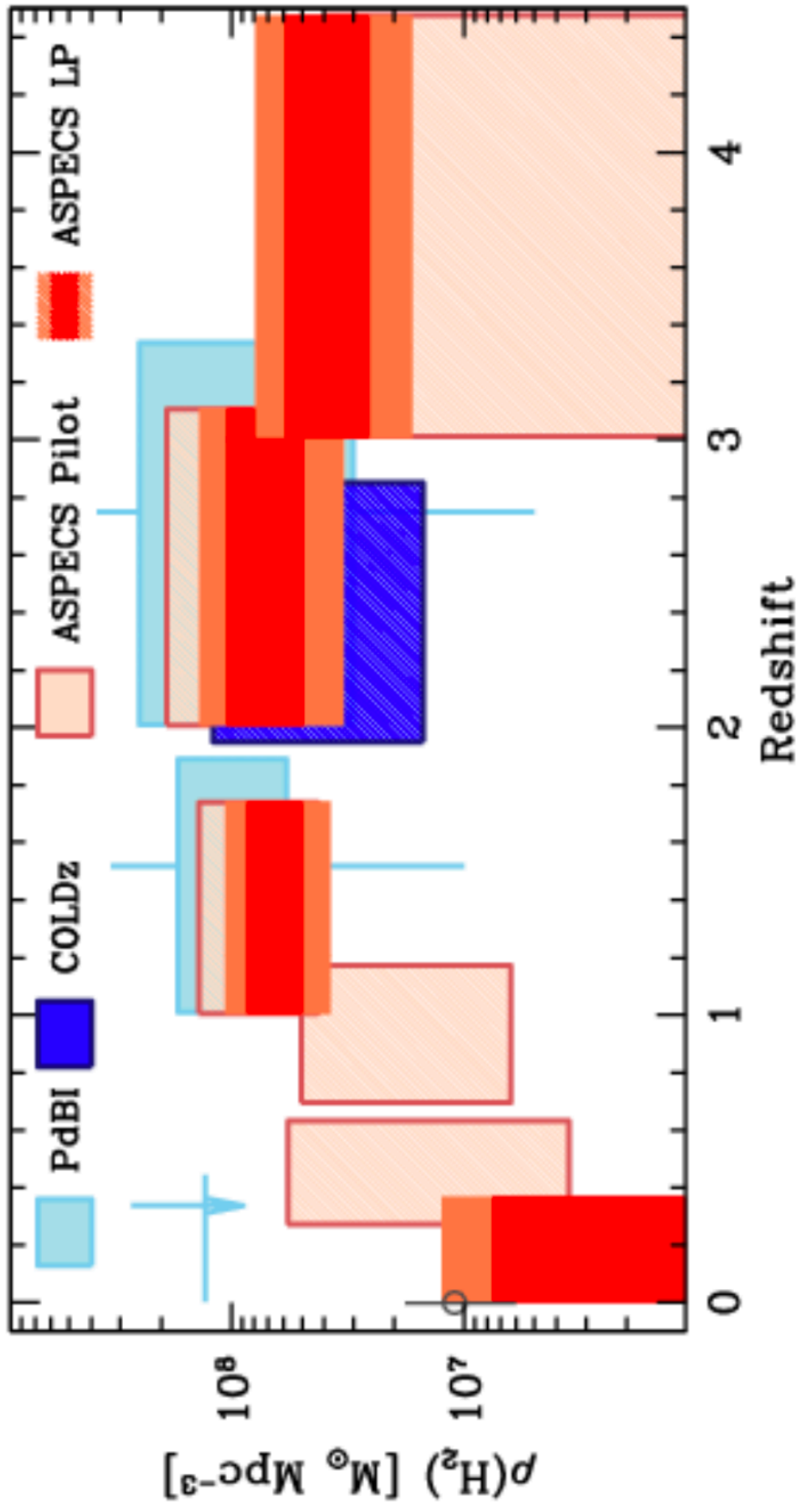
Summary

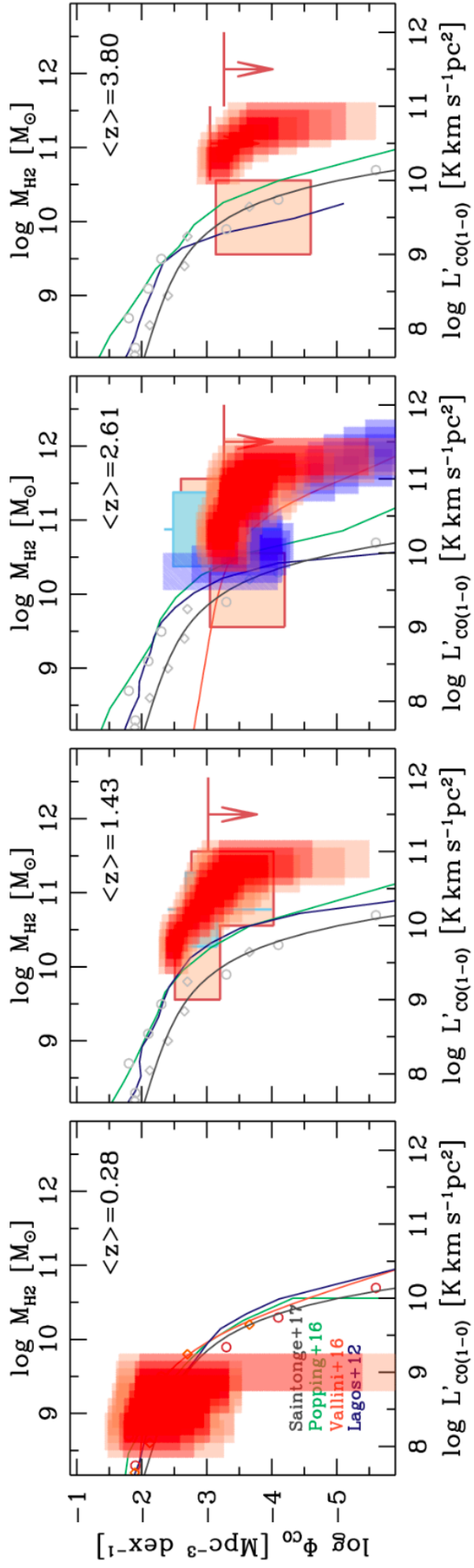
- I. Power spectrum measurement is broadly consistent with the observed luminosity functions. The inability to separate individual J transitions in the auto-power spectrum precludes any powerful constraints on the Schechter parameters for individual CO luminosity functions – these are better obtained with the individual detections – but the **power spectrum places significantly tighter constraints on the total CO power**.
- II. Cross-power spectrum indicates **that known optical galaxies in the full survey can account for the total observed CO shot noise power**, but there are **small-scale variations** wherein optical galaxies (w/out previously detected CO emission) can provide at least half of the observed CO power.











Line	Redshift	Volume [cMpc ³]	limit M_{H2} [10 ¹⁰ M _⊙]
(1)	(2)	(3)	(4)
CO(1-0)	0.003 – 0.369	338	0.11
CO(2-1)	1.006 – 1.738	8198	0.68
CO(3-2)	2.008 – 3.107	14931	1.8
CO(4-3)	3.011 – 4.475	18242	2.7

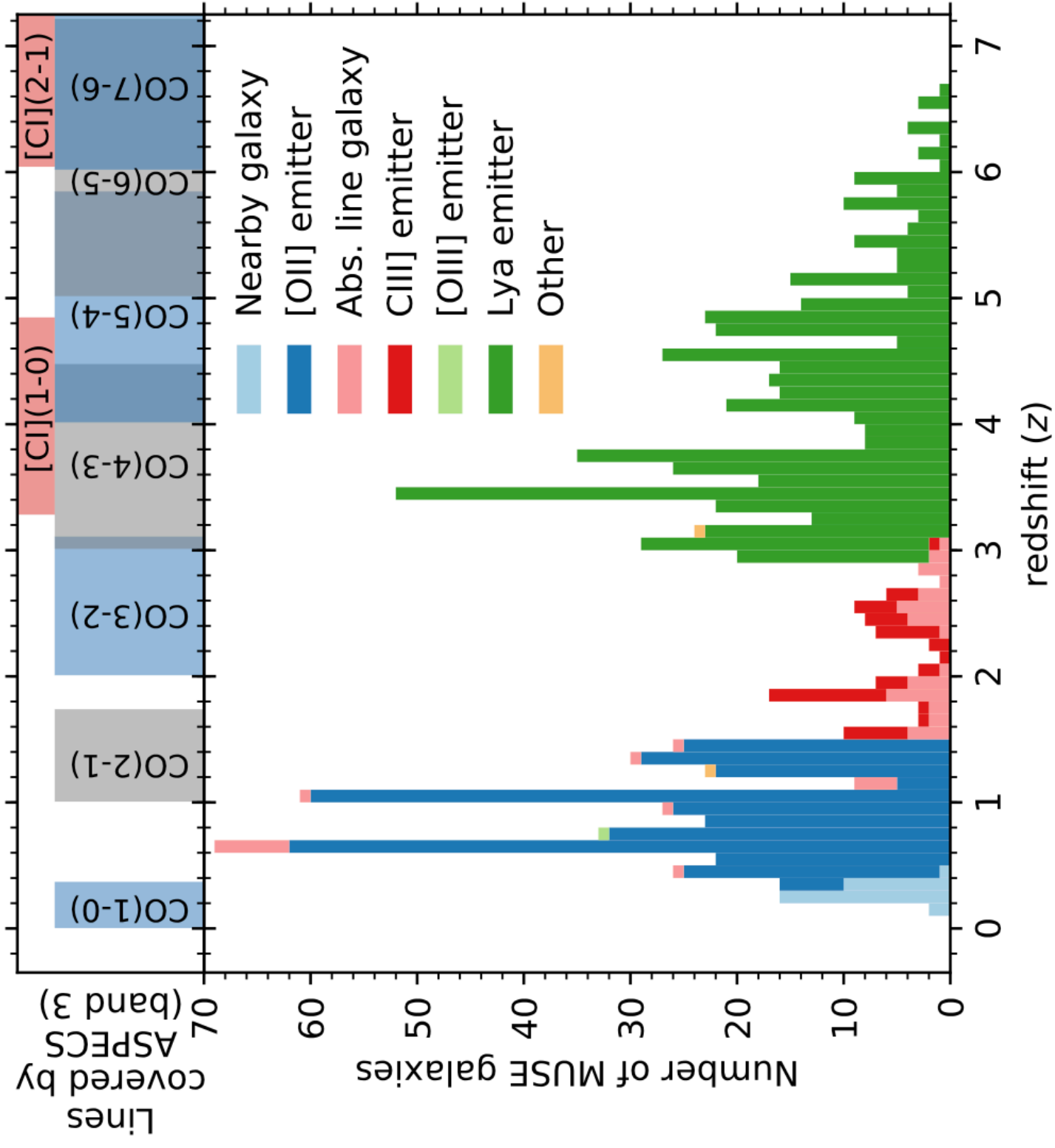


Table 2 Factors to calculate $L'_{\text{CO}(1-0)}$ from higher J transitions up to $J = 5^{\text{a}}$

Source	SMG	QSO	CSG	MW	M82
$L'_{\text{CO}(2-1)}/L'_{\text{CO}(1-0)}$	0.85	0.99	~ 0.9	0.5	0.98
$L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)}$	0.66	0.97	~ 0.6	0.27	0.93
$L'_{\text{CO}(4-3)}/L'_{\text{CO}(1-0)}$	0.46	0.87	–	0.17	0.85
$L'_{\text{CO}(5-4)}/L'_{\text{CO}(1-0)}$	0.39	0.69	–	0.08	0.75

Comparison between ASPECS in Band 3 as “traditional” galaxy survey (GS) and line intensity mapping (LIM) experiment

Let $L_{\min} = \gamma \sigma_N$ represent the minimum detectable luminosity in a traditional galaxy survey

For ASPECS, $\gamma \sim 7$ and $\langle \sigma_N \rangle = 0.196 \text{ mJy beam}^{-1}$ per 7.815 MHz channel, $L_{\min} = 9.85 \times 10^5 \text{ L}\odot$

$$\sim 2.5 \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$$

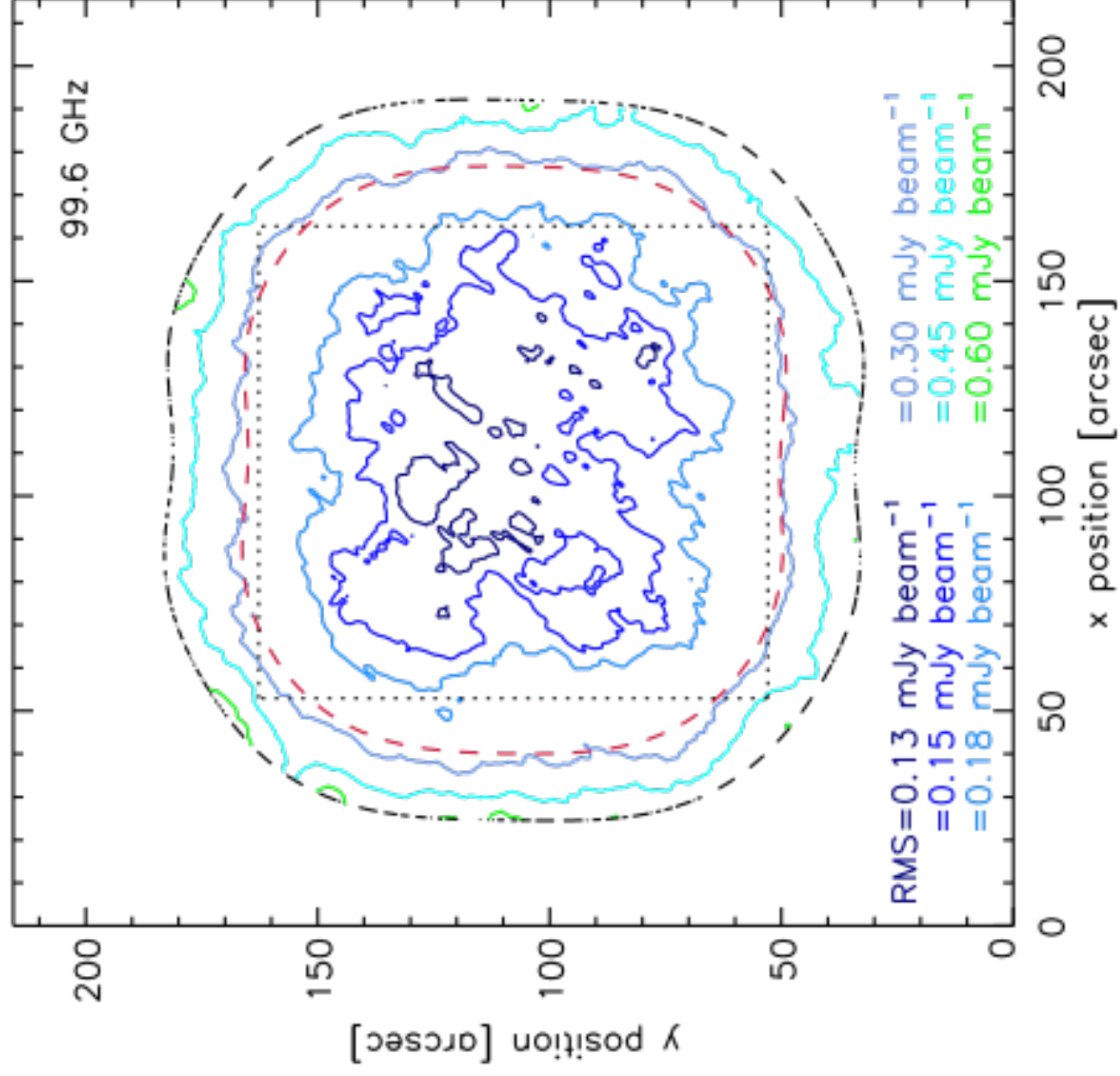
- GS mode: Integrating the CO Schechter LFs down to this $L_{\min}$ recovers 96-99% of total shot noise power per the observed LFs
- LIM mode: auto-power spectrum rules out a large range of total shot noise power predicted by the LFs, but is undetected (we report 3sigma UL)

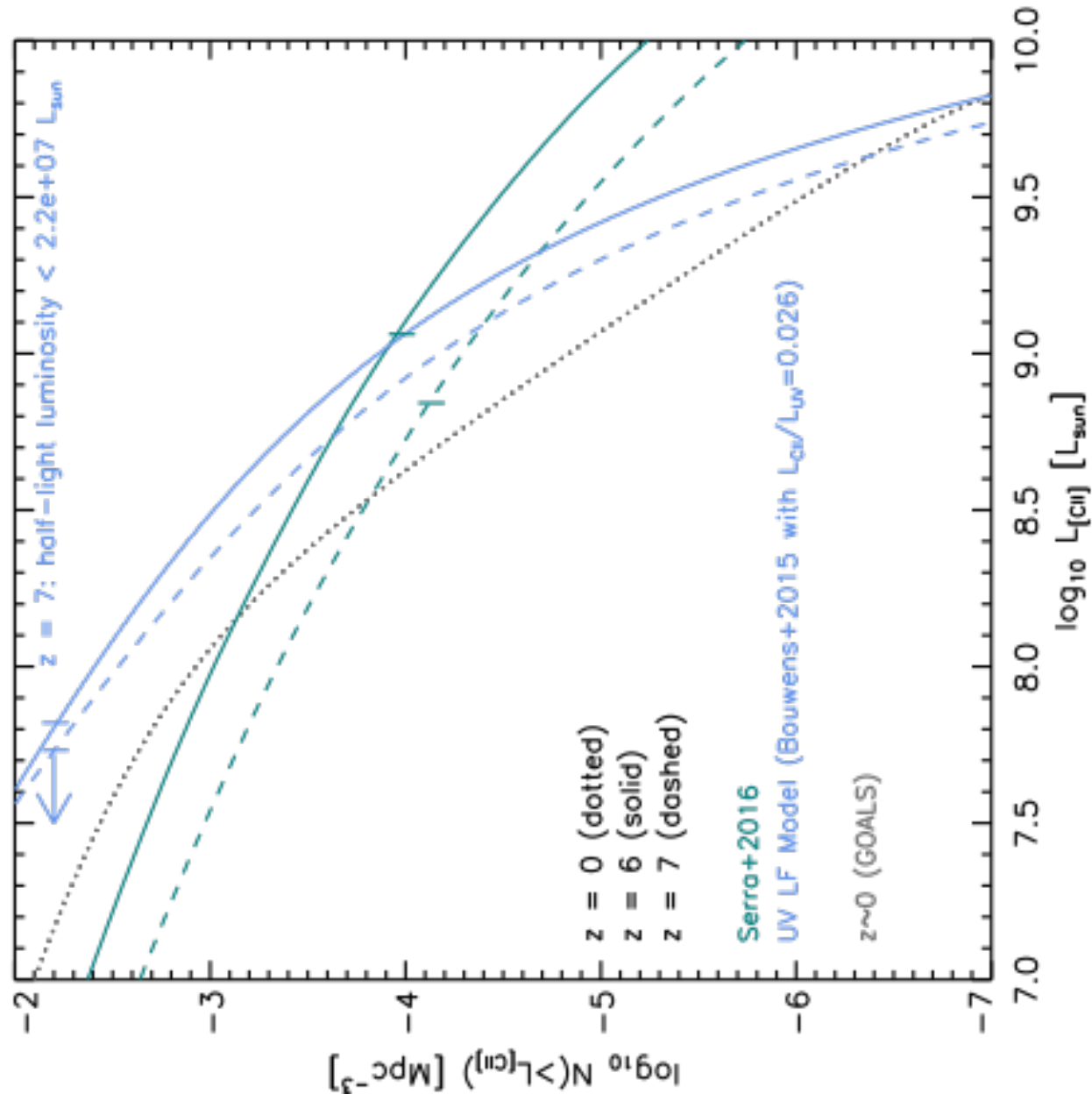
The SNR on the power spectrum can be related to γ , the total number of modes in the survey, and the number of detected galaxies in the survey:

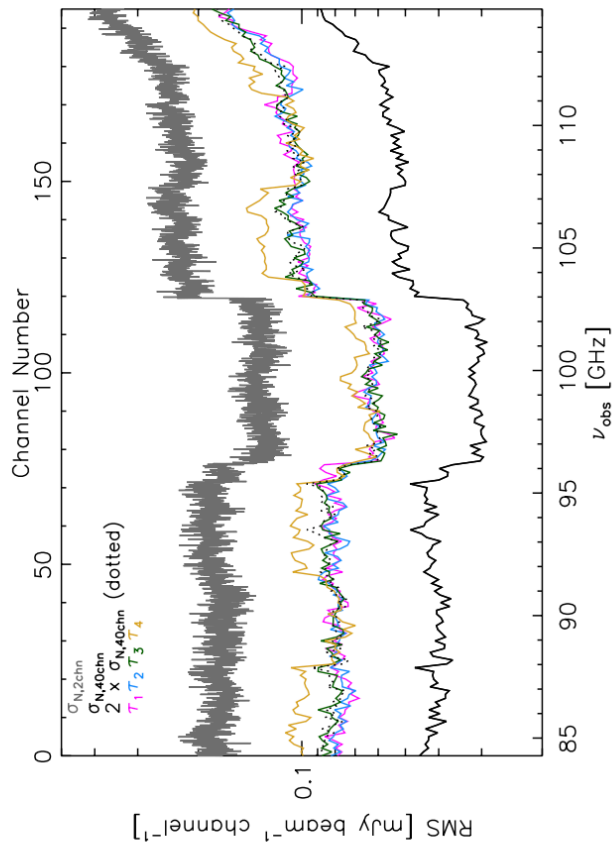
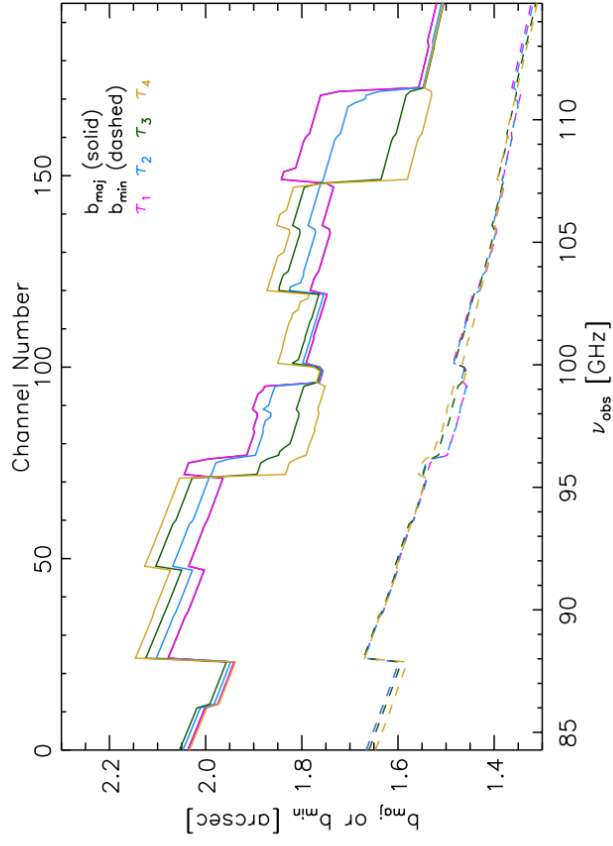
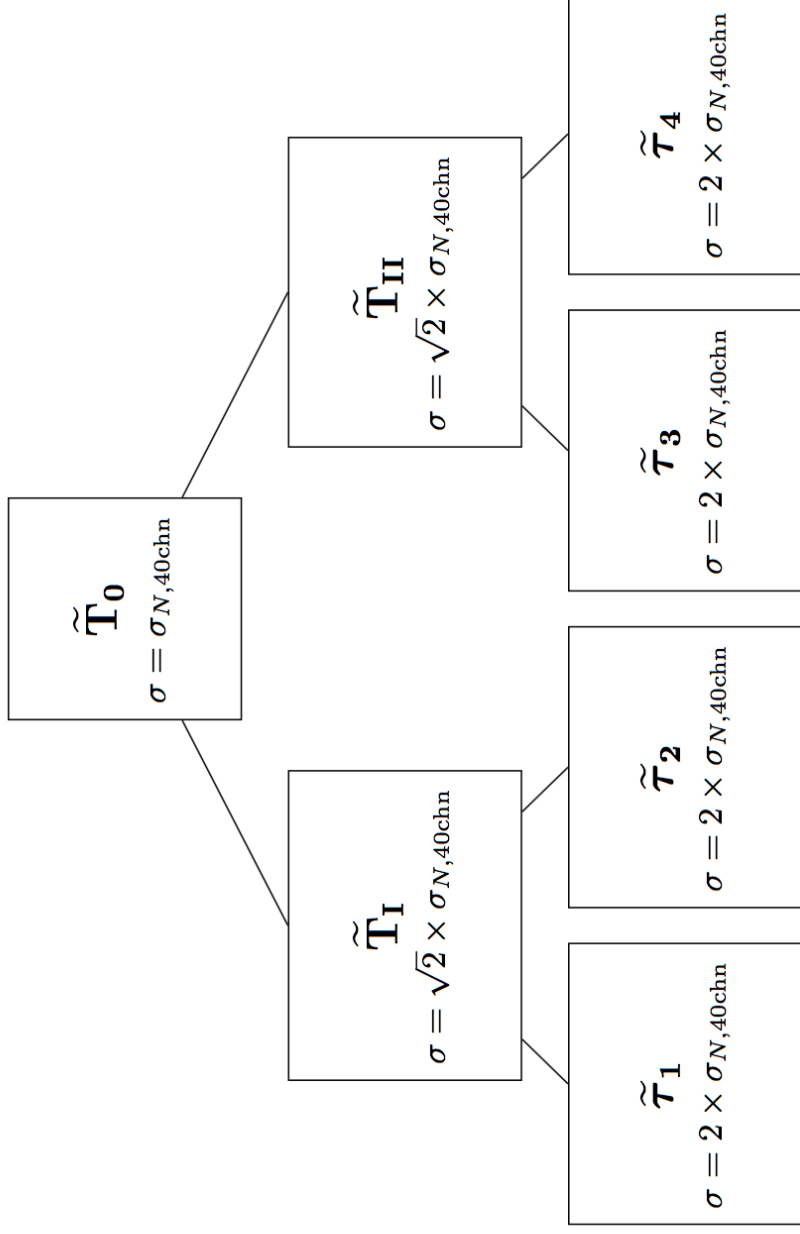
$$(\text{SNR})_{\text{LIM}} \propto \frac{N_{\text{gal,det}}}{\sqrt{N_m}}$$

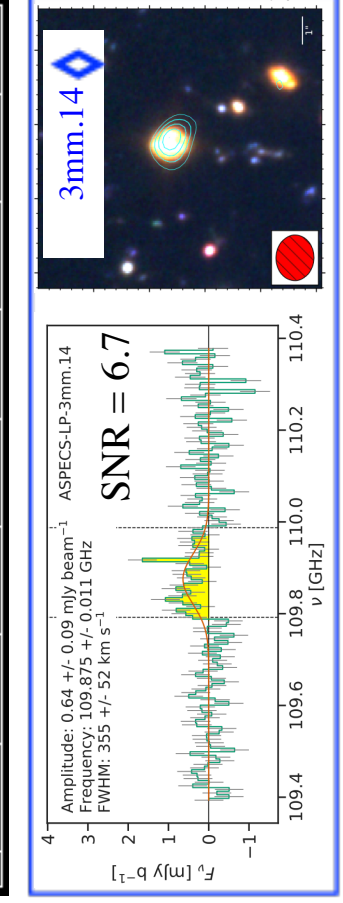
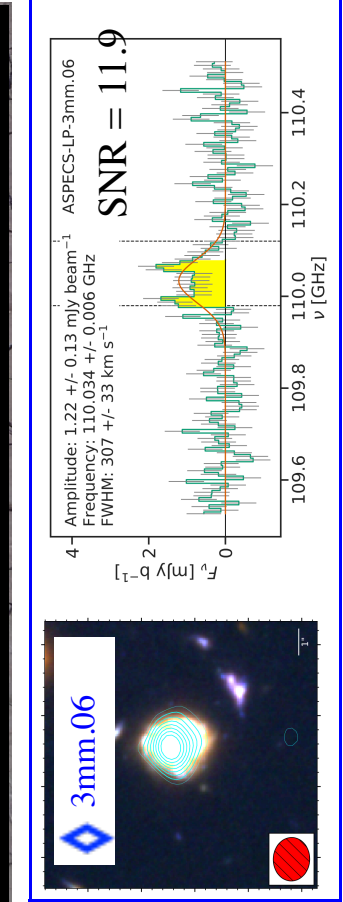
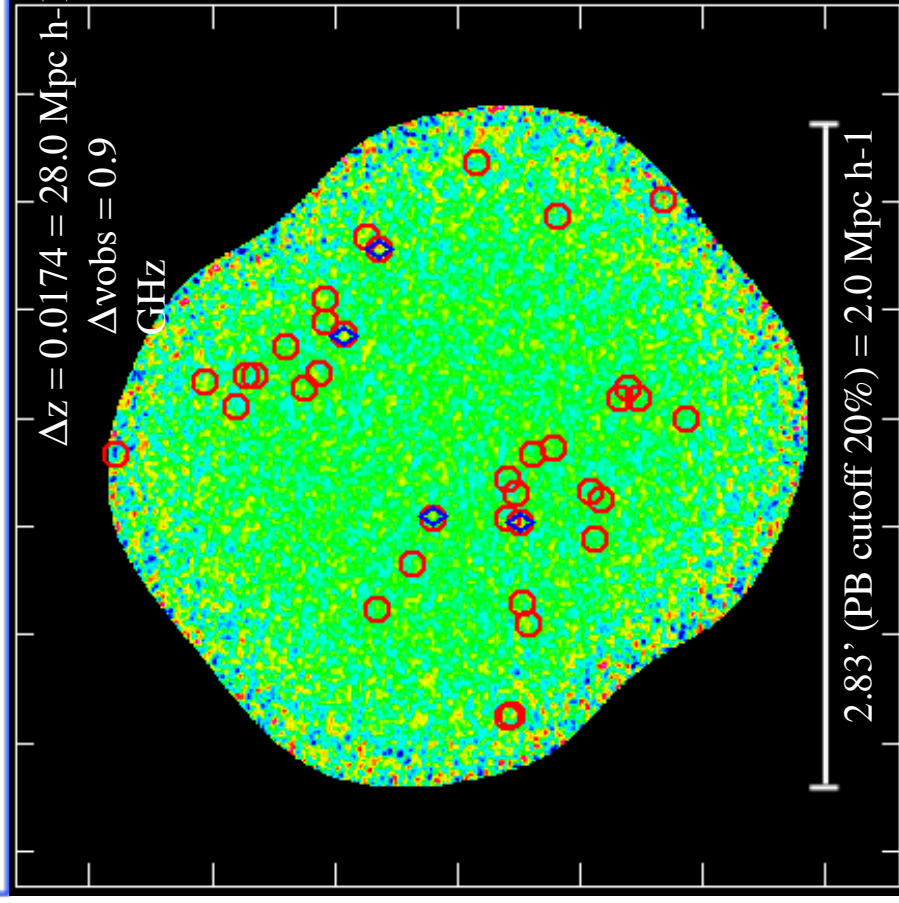
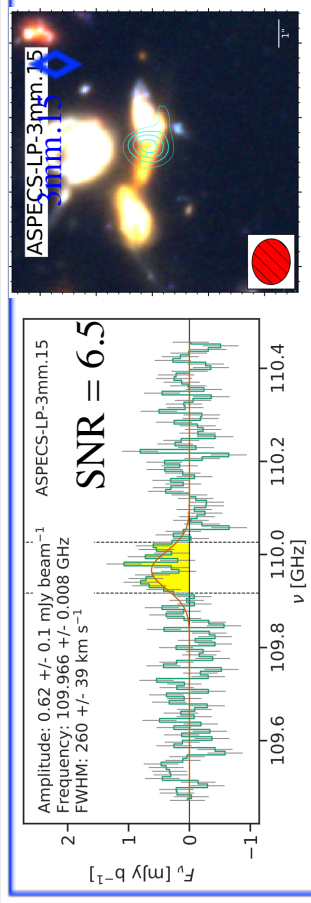
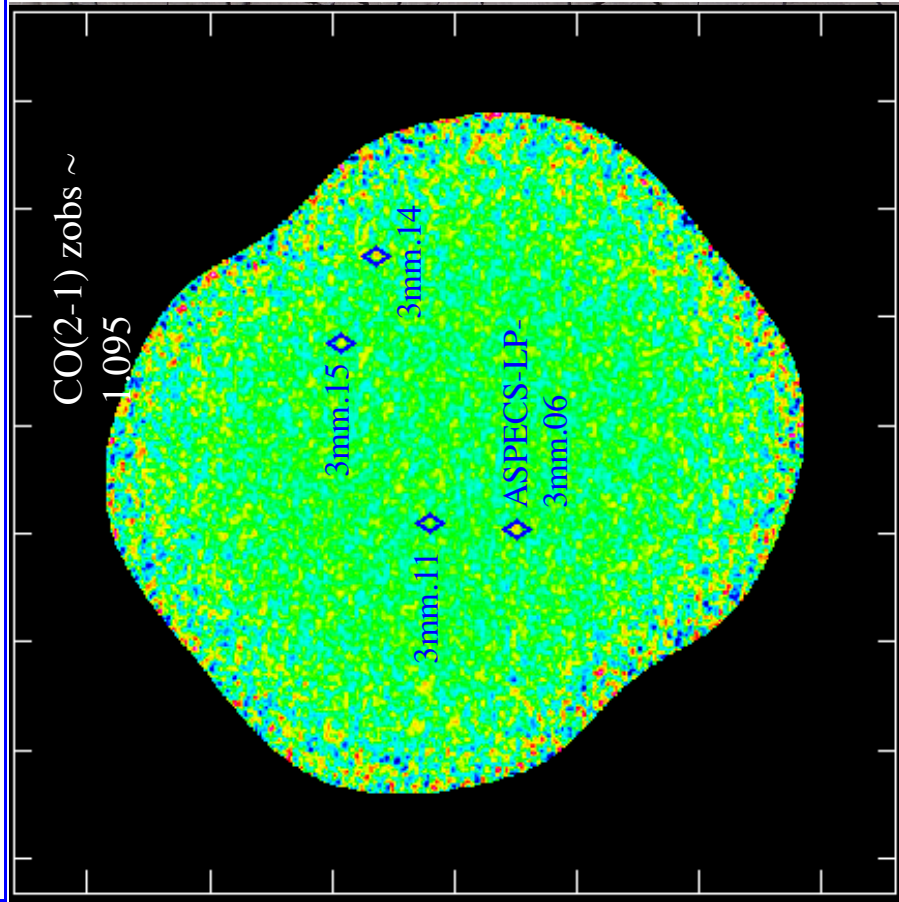
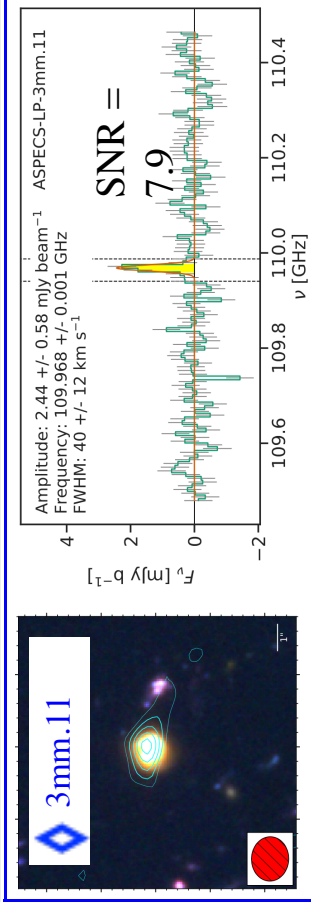
- $(\text{SNR})_{\text{LIM}} \sim 2$ for ASPECS Band 3 → individual galaxy counting is the optimal mode for measuring the shot noise power given the shape of the CO LFs and the ASPECS survey depth at the relevant redshifts

Without altering the LFs or survey depth, can we improve $(\text{SNR})_{\text{LIM}}$ so as to match or surpass $(\text{SNR})_{\text{GS}}$?









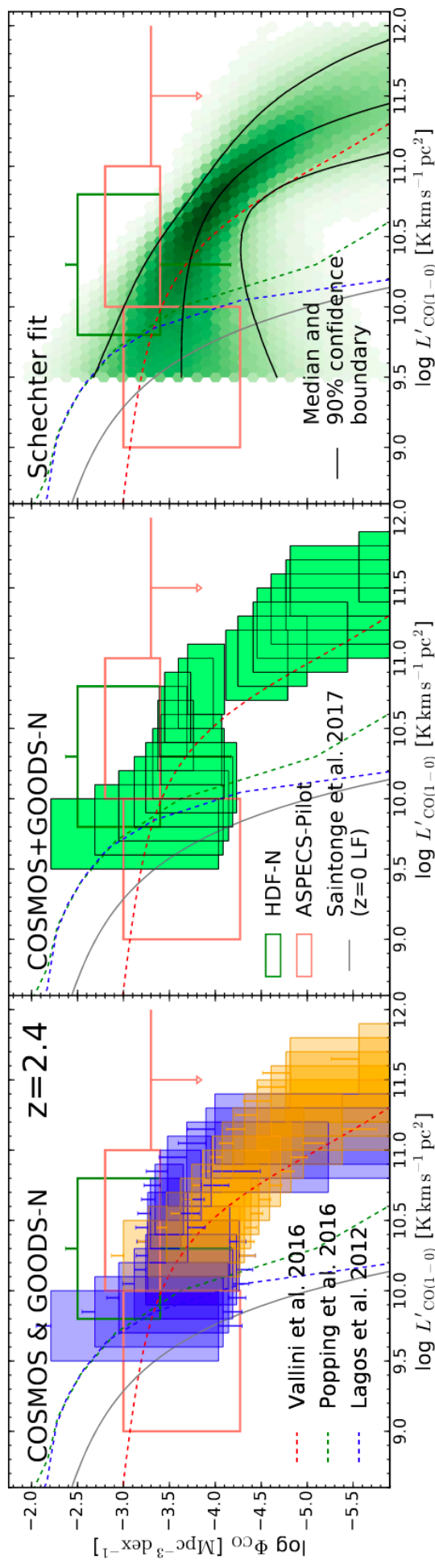


Figure 3. Comparison between the two COLDz survey fields and combined constraints on the CO($J=1 \rightarrow 0$) luminosity function. *Left:* Same as Fig. 2, top and middle right, but showing the COSMOS and GOODS-North constraints overlaid with each other. *Middle:* Same as Fig. 2, bottom right, combining the measurement from both fields, for comparison. *Right:* Density of Schechter function fits to the combined data, as distributed according to the fit parameter distributions as obtained with the ABC method (shaded region). Darker colors represent higher probabilities. For reference, solid black lines show the median and 90% confidence boundary of the implied luminosity function distributions (see Tab. 2 for corresponding Schechter parameters). All except the COLDz data are the same as in Fig. 2 in all panels.