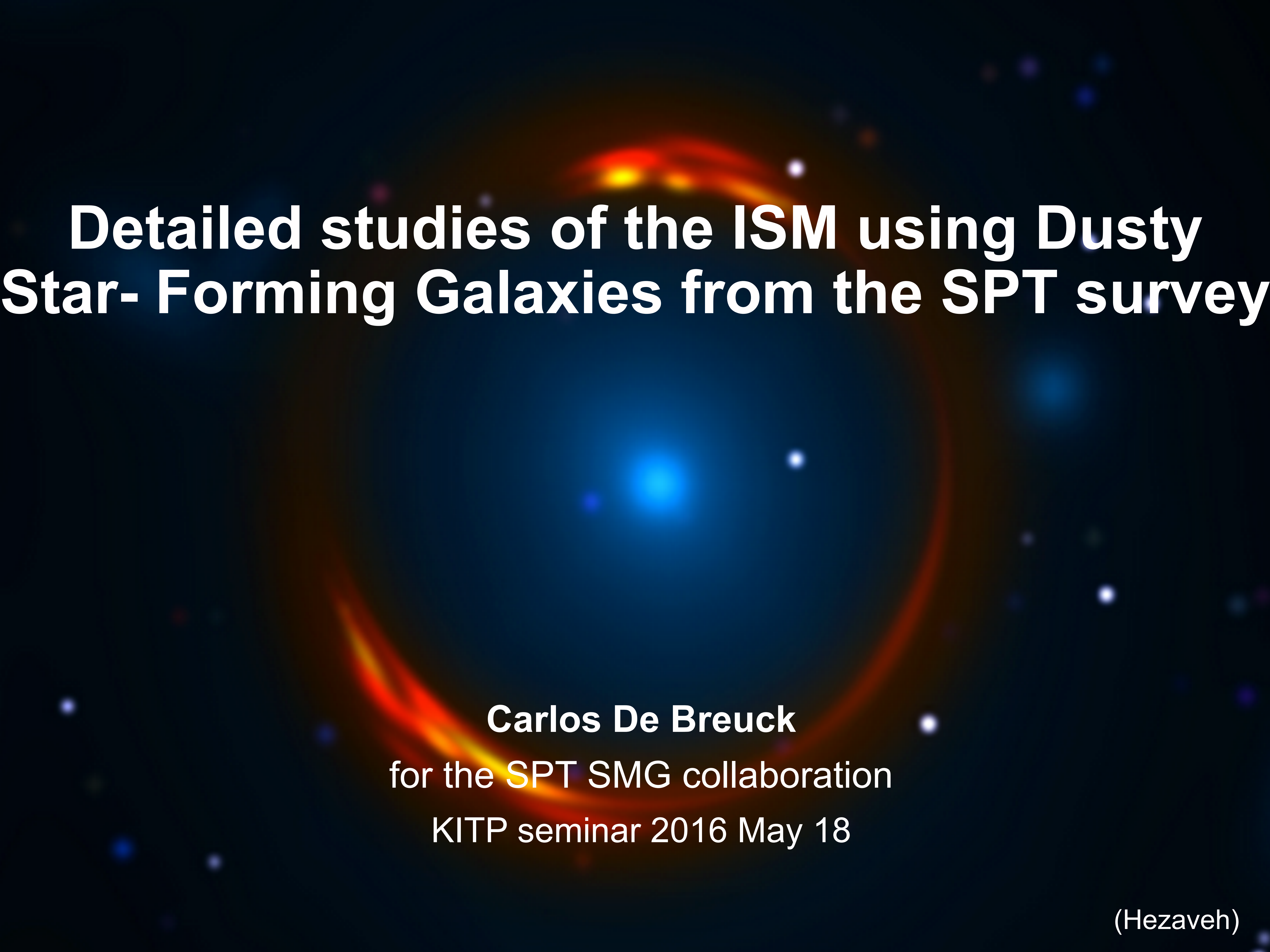
Detailed studies of the ISM using Dusty Star- Forming Galaxies from the SPT survey

Carlos De Breuck

for the SPT SMG collaboration

KITP seminar 2016 May 18



(Hezaveh)

SPT Submillimeter Galaxy Collaboration

James Aguirre (U. Penn)
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Matt Ashby (CfA)
Matthieu Bethermin (ESO)
Matt Bothwell (Cambridge)
Mark Brodwin (U. Missouri)
John Carlstrom (U. Chicago)
Scott Chapman (Dalhousie)
Tom Crawford (U. Chicago)

Carlos De Breuck (ESO)
Chris Fassnacht (UC Davis)
Anthony Gonzalez (U. Florida)
Thomas Greve (UCL)
Bitten Gullberg (ESO → Durham)
Yashar Hezaveh (Stanford)
Jingzhe Ma (U. Florida)
Matt Malkan (UCLA)
Dan Marrone (U. Arizona)

Eric Murphy (IPAC)
Kaja Rotermund (Dalhousie)
Justin Spilker (U. Arizona)
Brian Stalder (Harvard)
Antony Stark (CfA)
Maria Strandet (MPIfR)
Joaquin Vieira (U. Illinois)
Axel Weiss (MPIfR)
Niraj Welikala (Oxford)

Outline

The SPT-DSFGs

Lensing models

The redshift search & distribution

The APEX [CII] survey

Other CO and fine-structure lines

Conclusion

The South Pole Telescope survey

PI: John Carlstrom

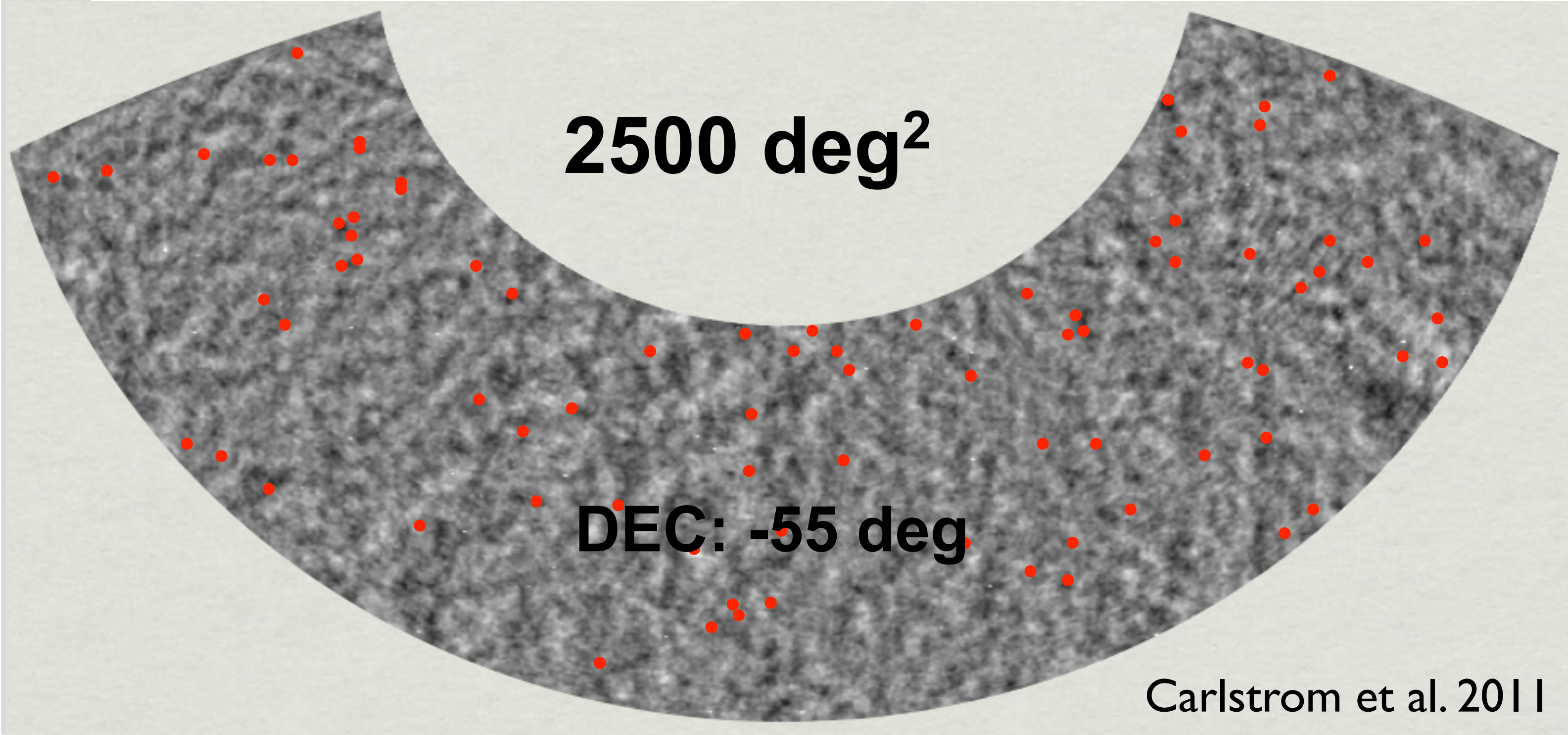
Goal: Cosmological survey to study CMB fine structure and Sunyaev–Zel'dovich signal from Galaxy clusters

Area: 2500 deg^2

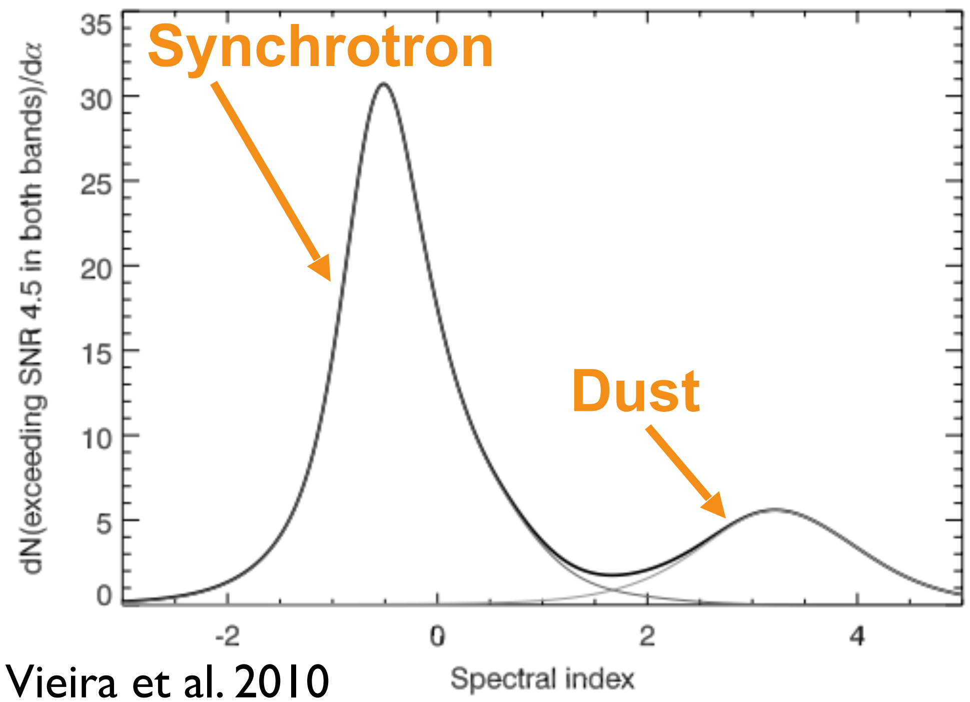
Wavelengths: 3, 2 and 1.4 mm (typical rms at 1 mm ~3.5 mJy)

Bonus: Large sample of rare ultra bright sources

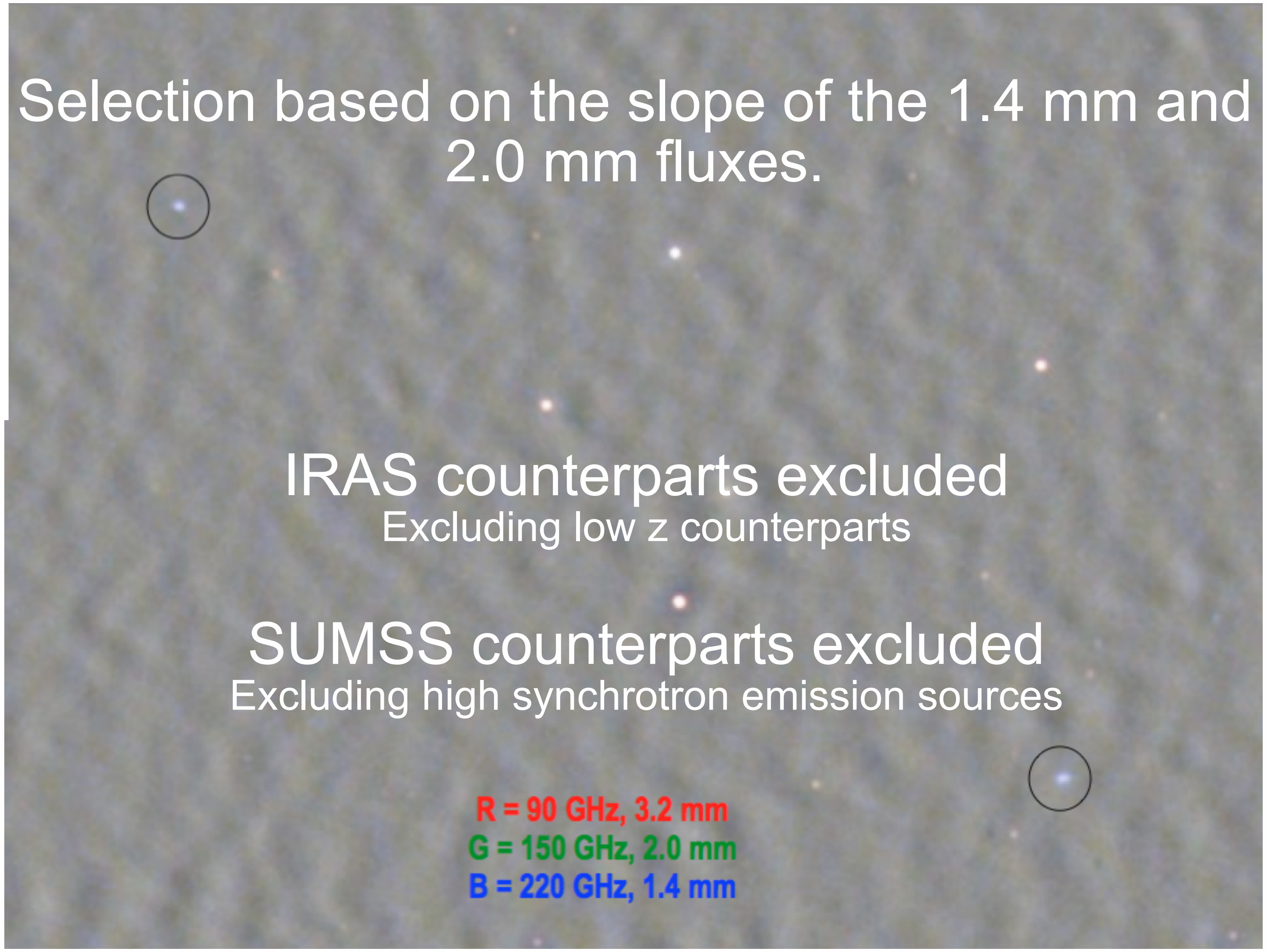
Funded by NSF



The SPT SMGs



Vieira et al. 2010



Selection based on the slope of the 1.4 mm and 2.0 mm fluxes.

IRAS counterparts excluded
Excluding low z counterparts

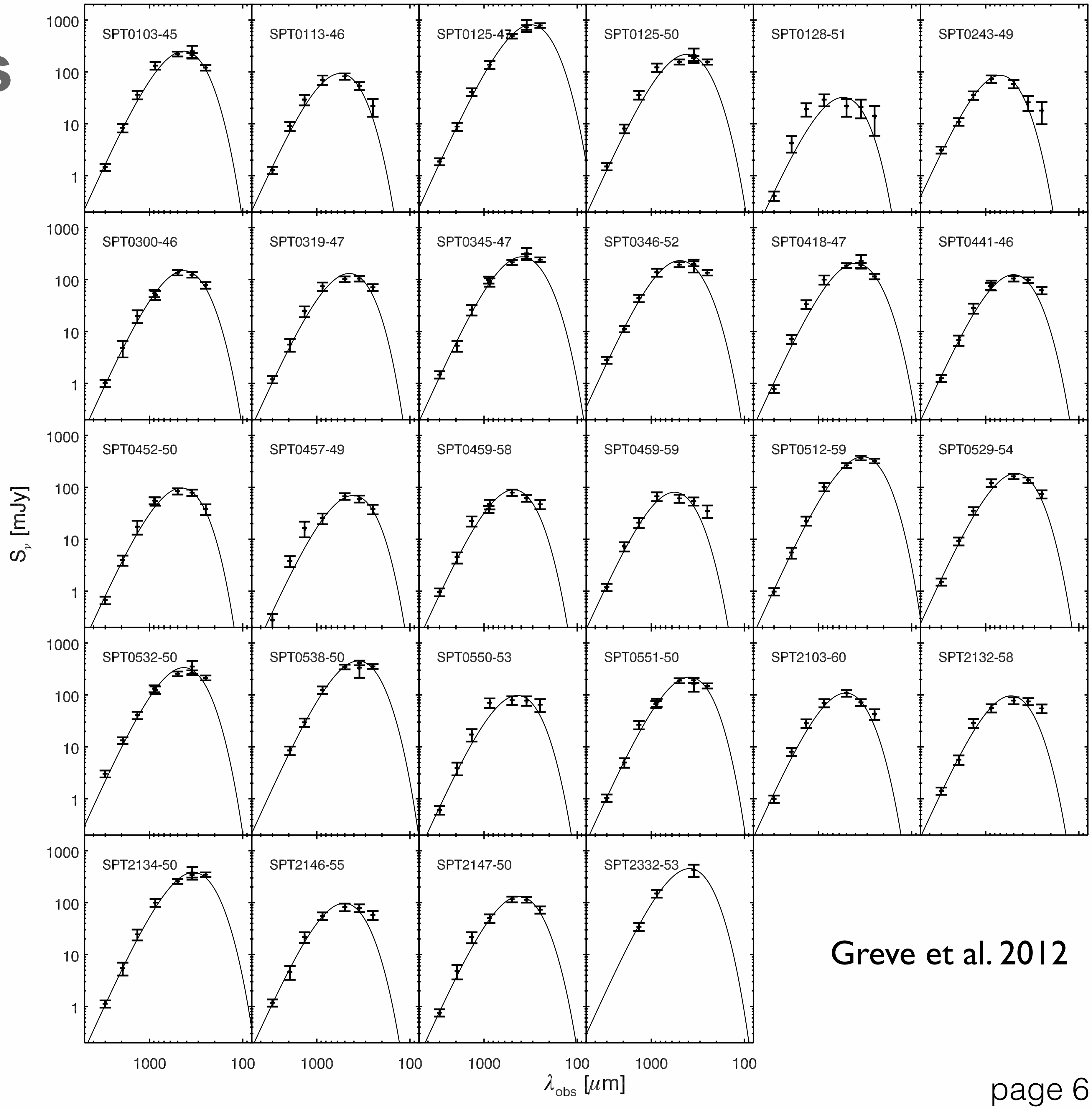
SUMSS counterparts excluded
Excluding high synchrotron emission sources

112 sources with $S_{1.4mm}$ > 15 mJy

10-band SEDs

- SPT 3, 2, 1.4mm
- LABOCA 850μm
- SPIRE 500, 350, 250μm
- PACS 160, 100, 70μm

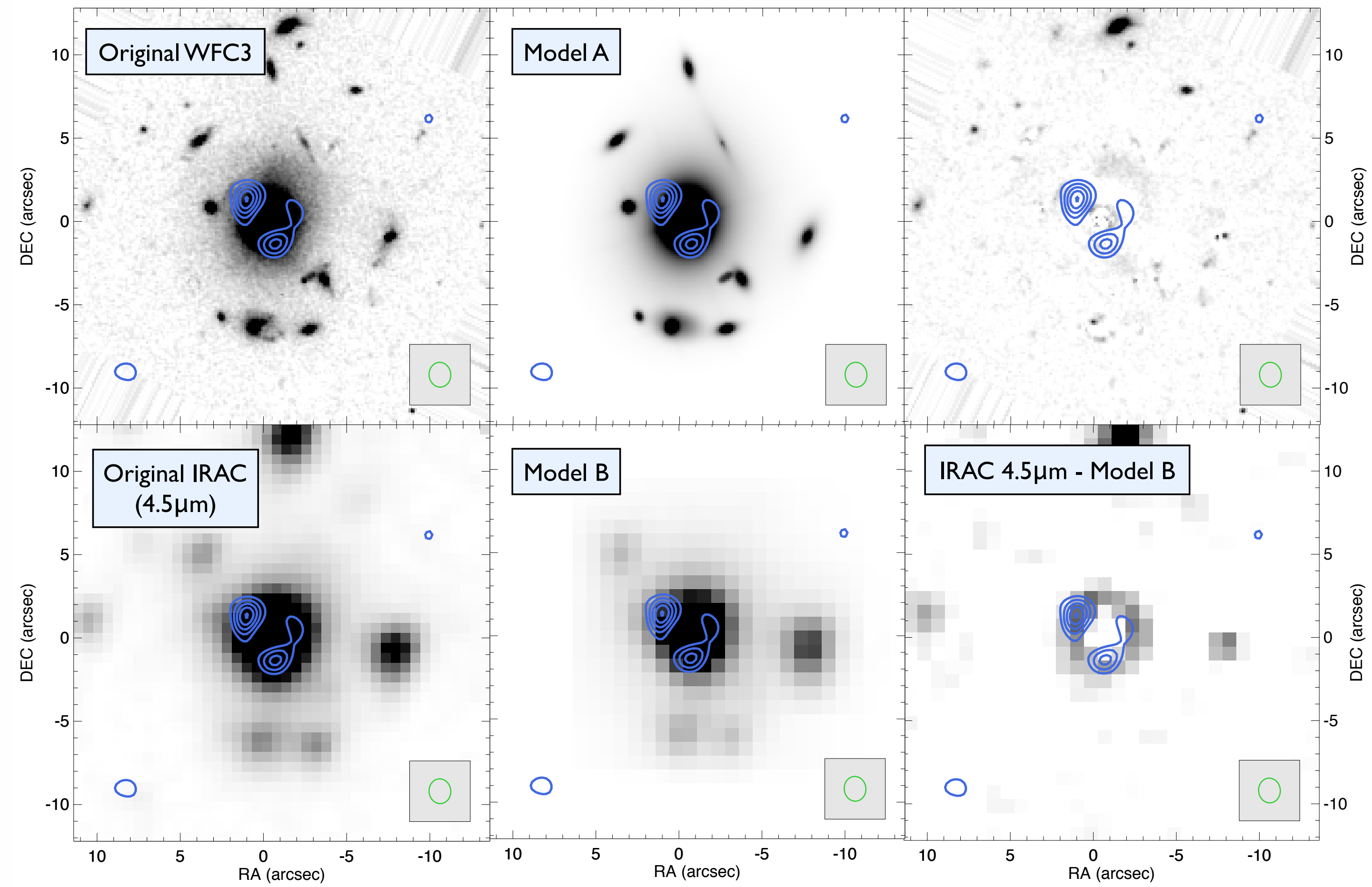
Thomas Greve

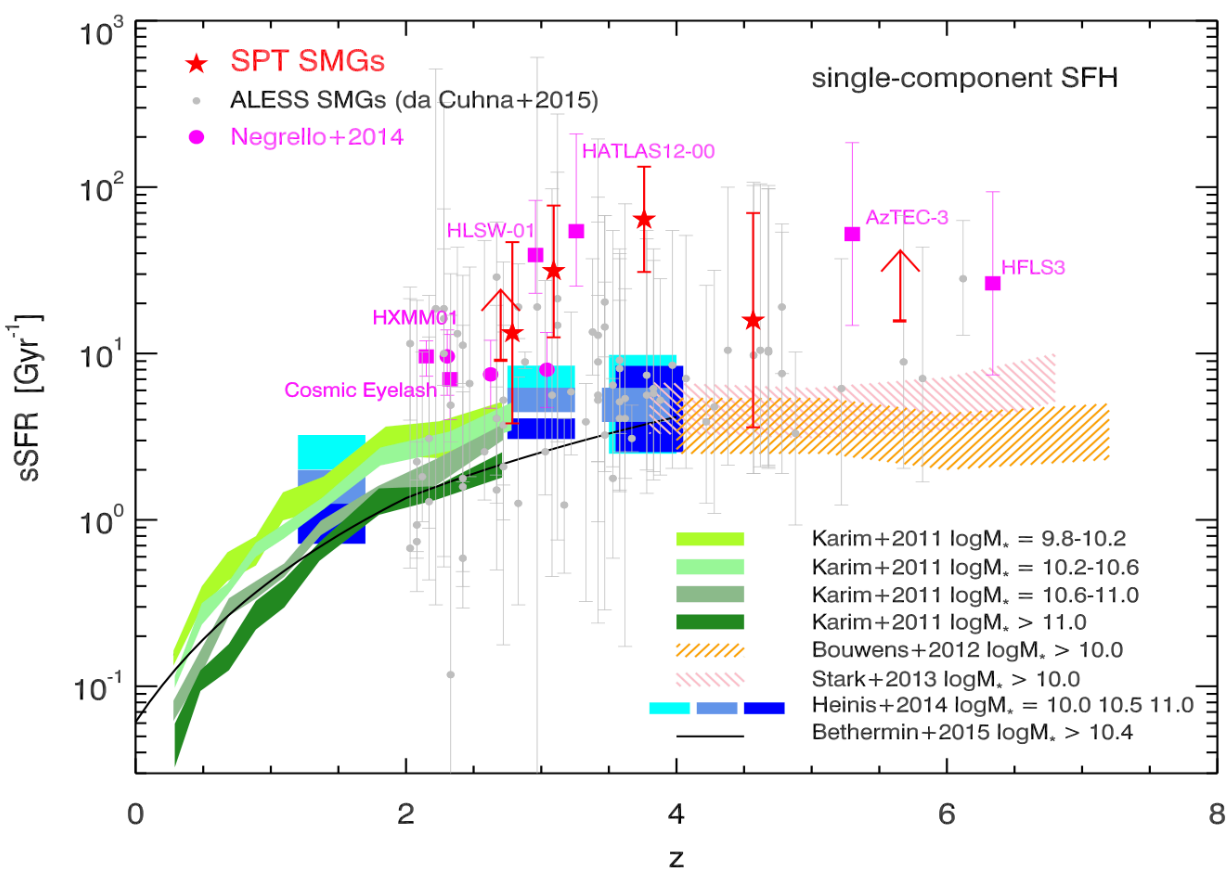


Greve et al. 2012

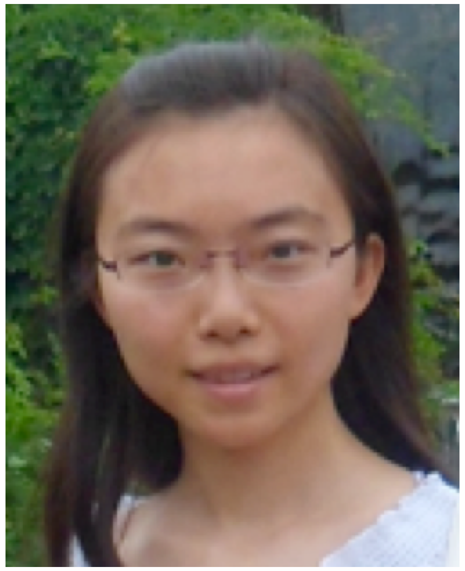
Stellar masses

- Complicated due to foreground lens dominating in the optical.
- Use HST imaging to model and deblend IRAC images.
- SPT DSFGs appear slightly above the main sequence.





Ma et al. 2015



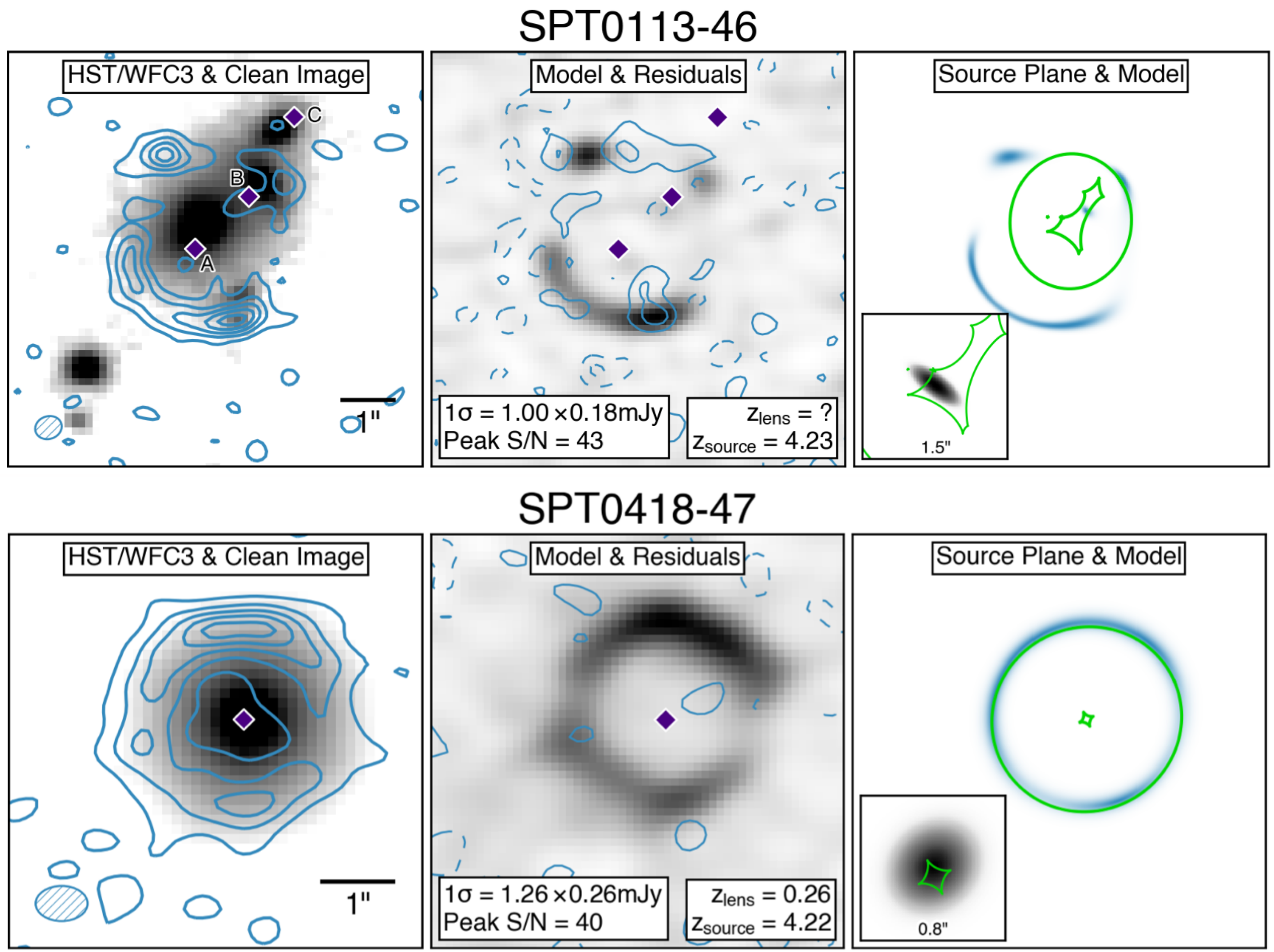
Jingzhe Ma

Lensing models based on ALMA

Justin Spilker

Yashar Hezaveh

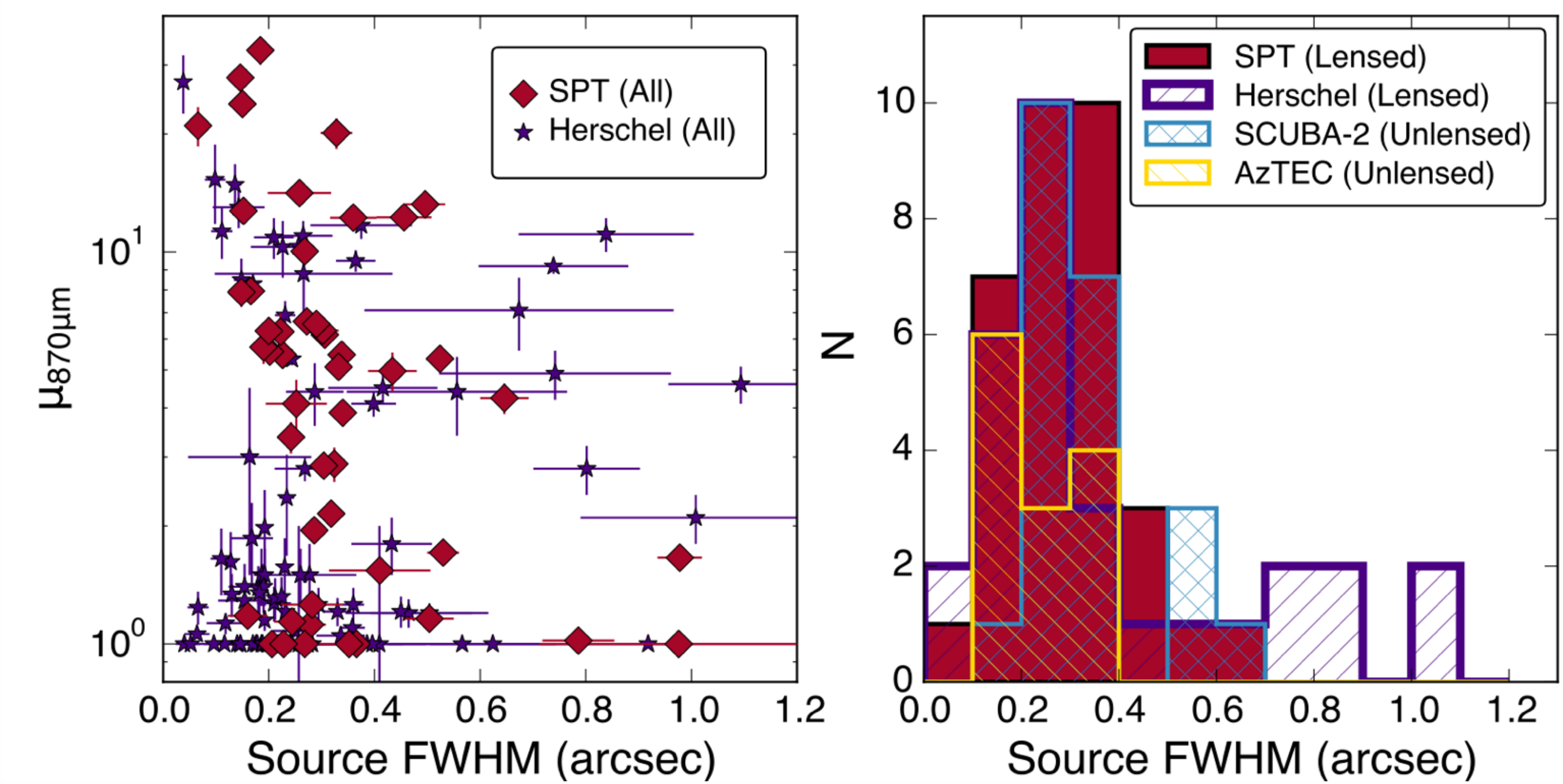
Dan Marrone



Lens modeling done in uv-plane: correct handling of phase errors

Spilker et al. 2016

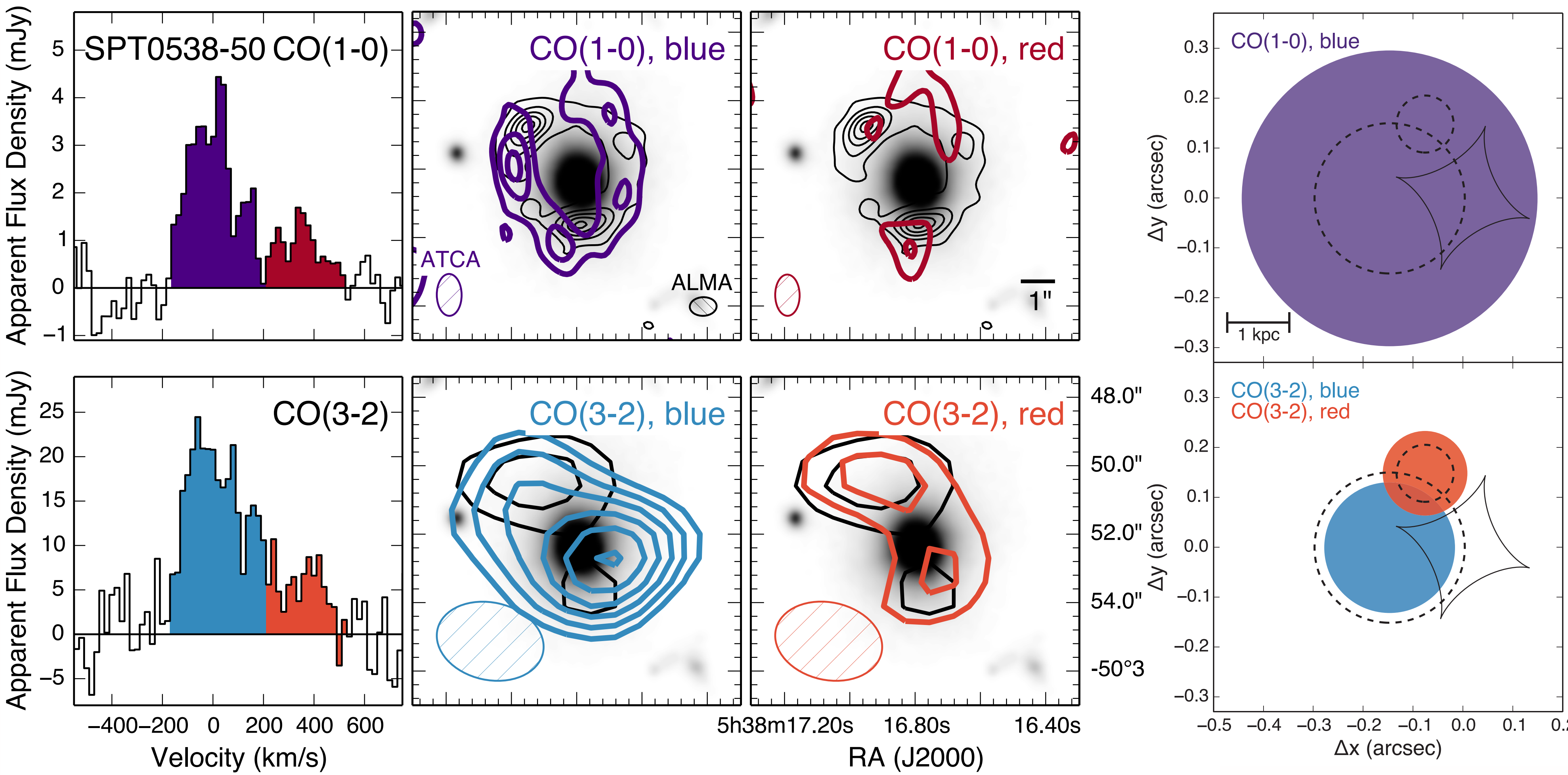
Physical parameters from lensing models



- Magnifications μ up to 30, median 6.3.
- Size distribution similar to unlensed samples.
- Allows to study surface brightness distributions.

Spilker et al. 2016

Resolved CO(1-0) & (3-2) models with ATCA

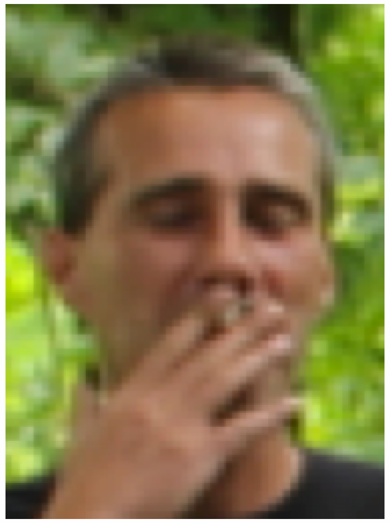


- Evidence for a major merger.
- Separation of 1.3 kpc possible thanks to lensing.
- Next step: 0.3” [CII] mapping with ALMA to obtain resolved Schmidt-Kennicutt diagrams.

Spilker et al. 2015

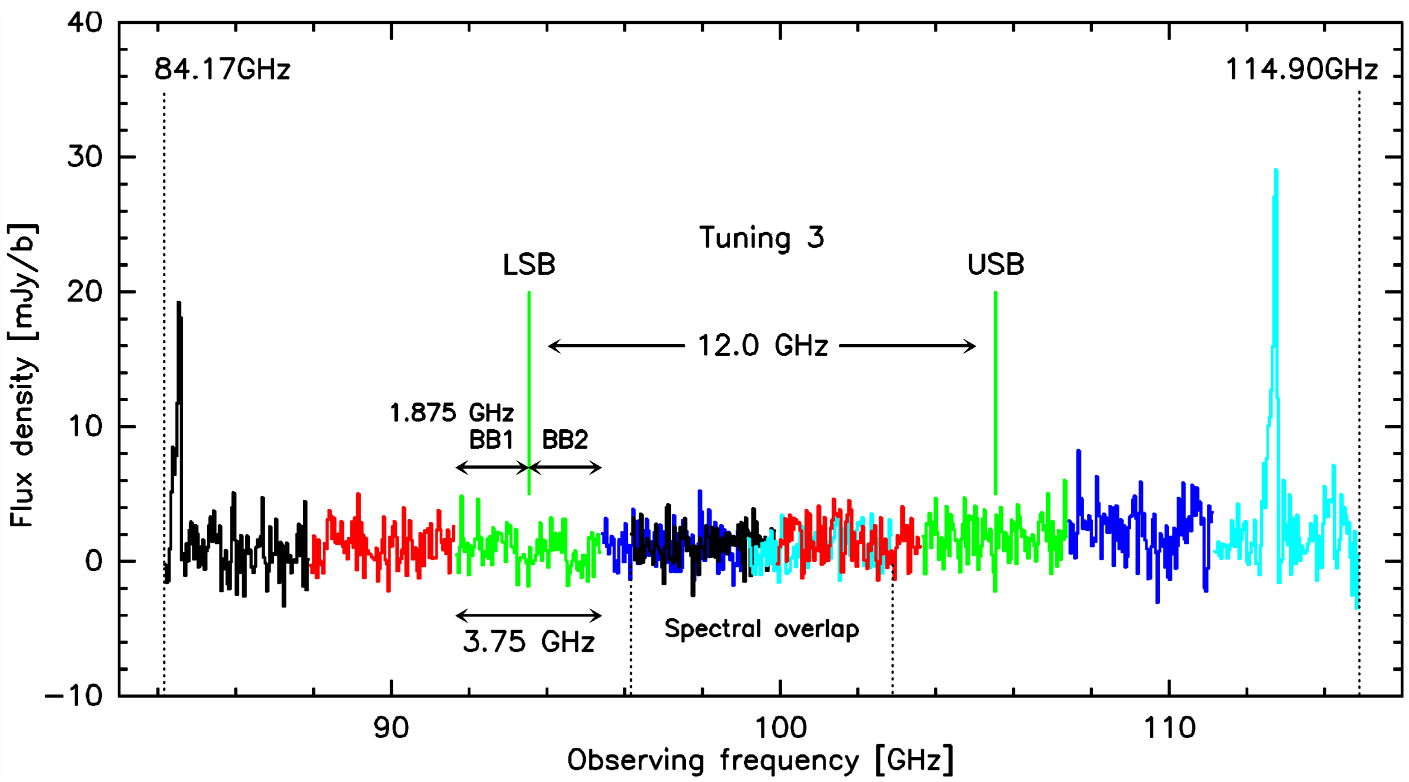
Blind redshift survey with ALMA

Maria Strandet



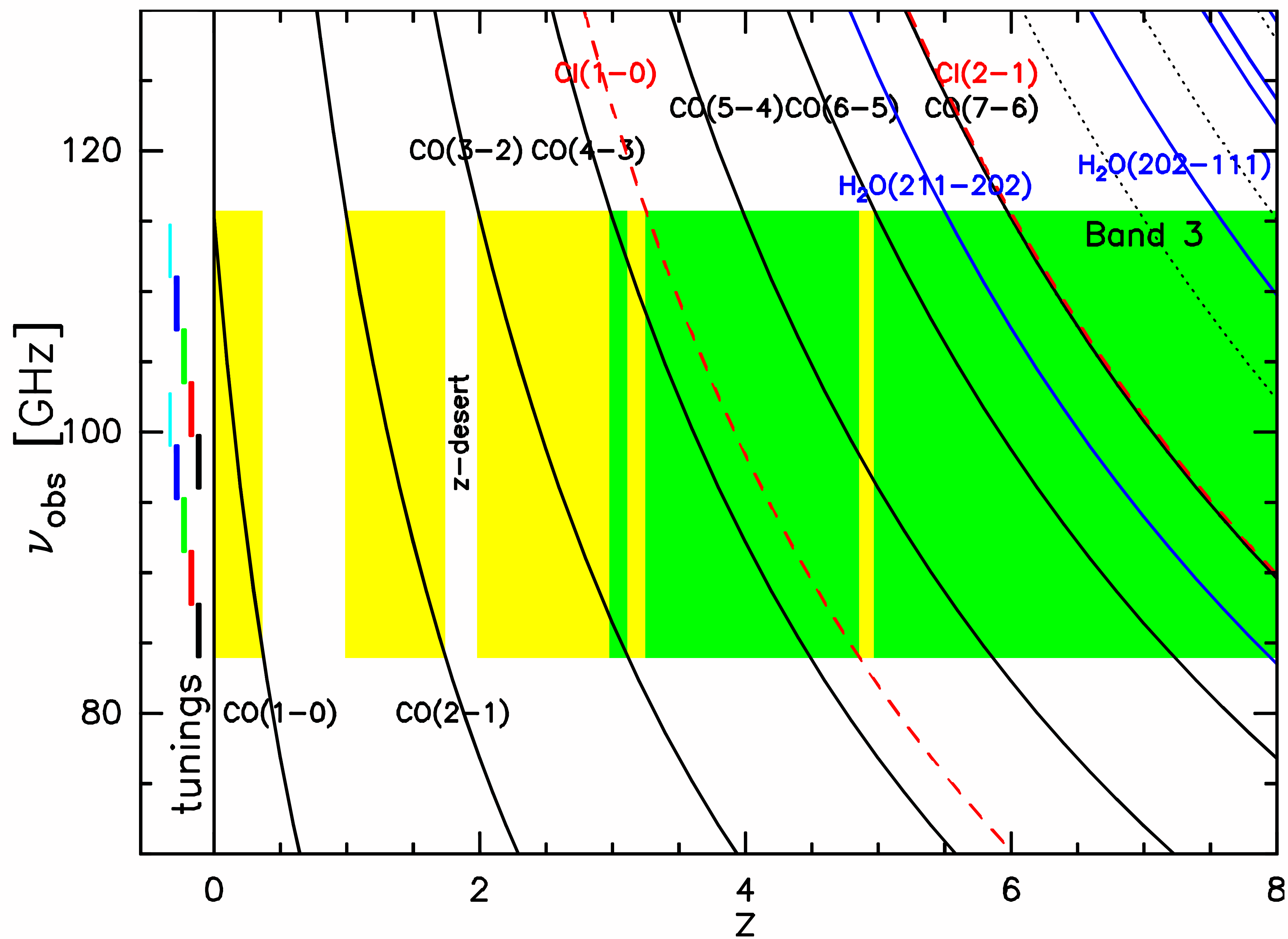
Axel Weiß

No problem with
counterpart identification



5 tunings
2 mJy @ 100km/s
Cy0 -**19 min** per source (16 antennas)
Cy1 - **10 min** per source (32 antennas)
Cy3 - **10 min** per source (36 antennas)

ALMA band 3 as a redshift machine



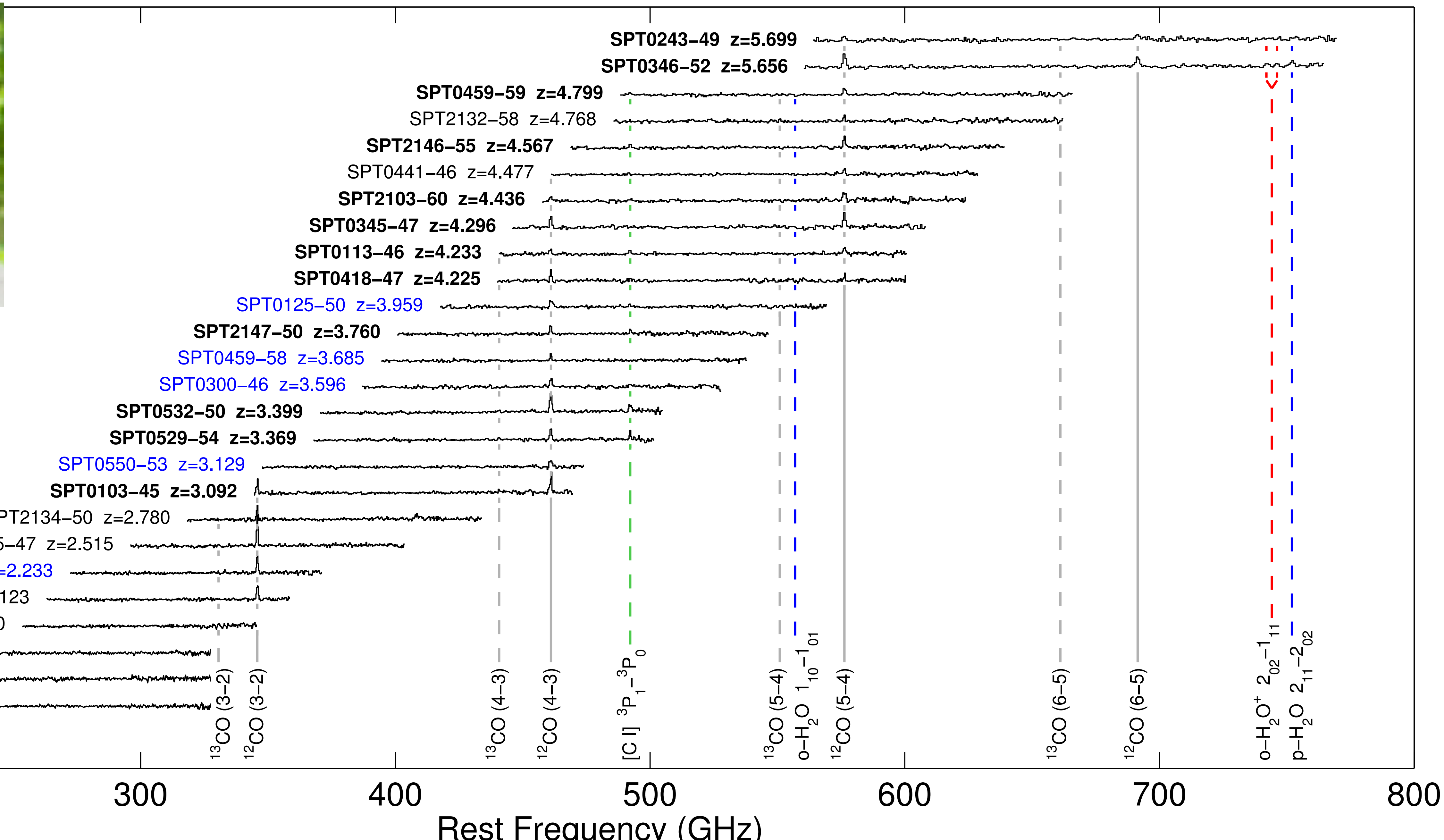
= 0 lines, *z* desert

= 1 line, ambiguous *z*

= 2 lines, unambiguous *z*

Overview of ALMA Cycle 0 spectra

Joaquin Vieira



Vieira *et al.* 2013 Nature

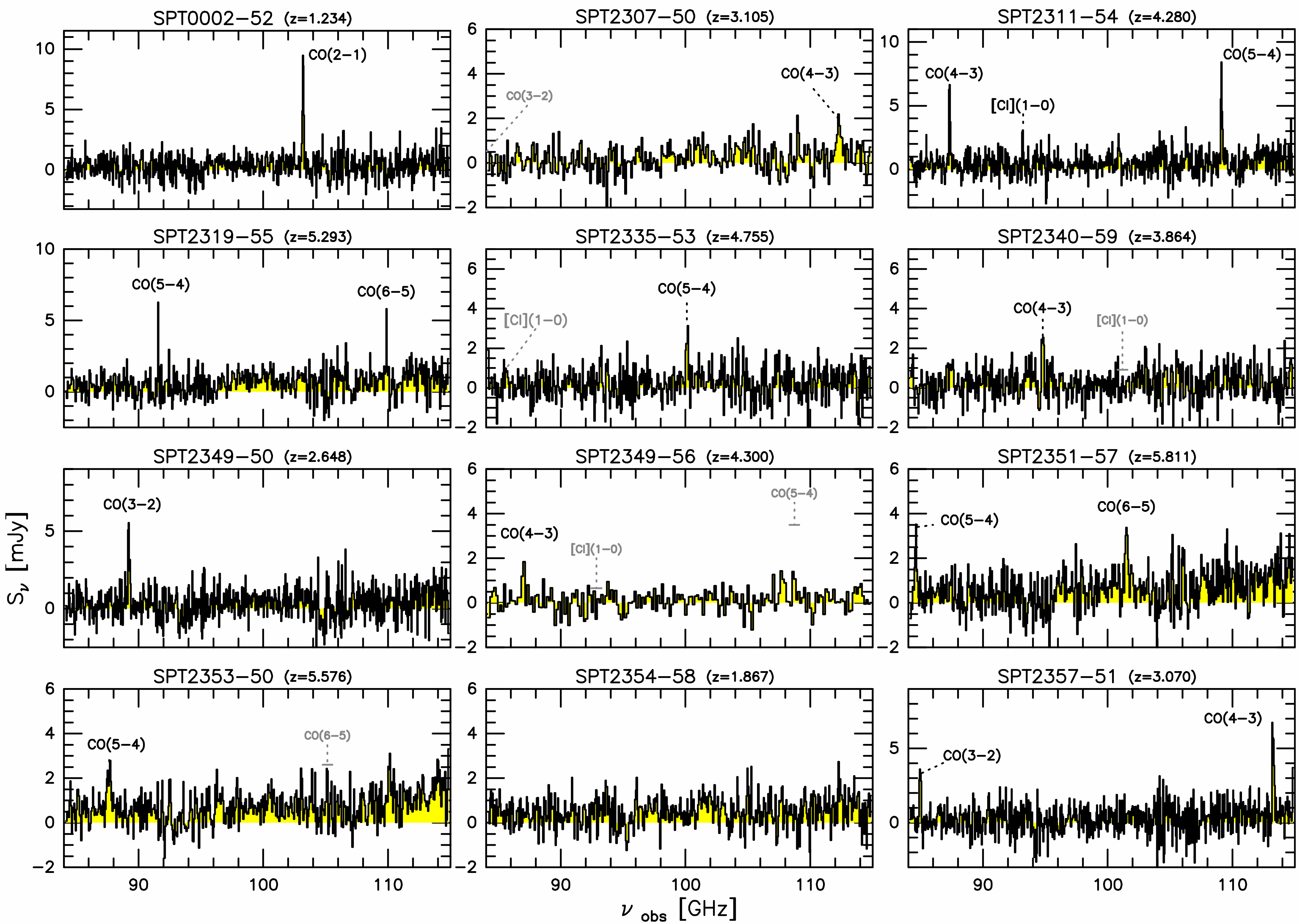
Bold = unambiguous redshift from ALMA

black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

blue = single line detected with redshift, most likely redshift from photo-z

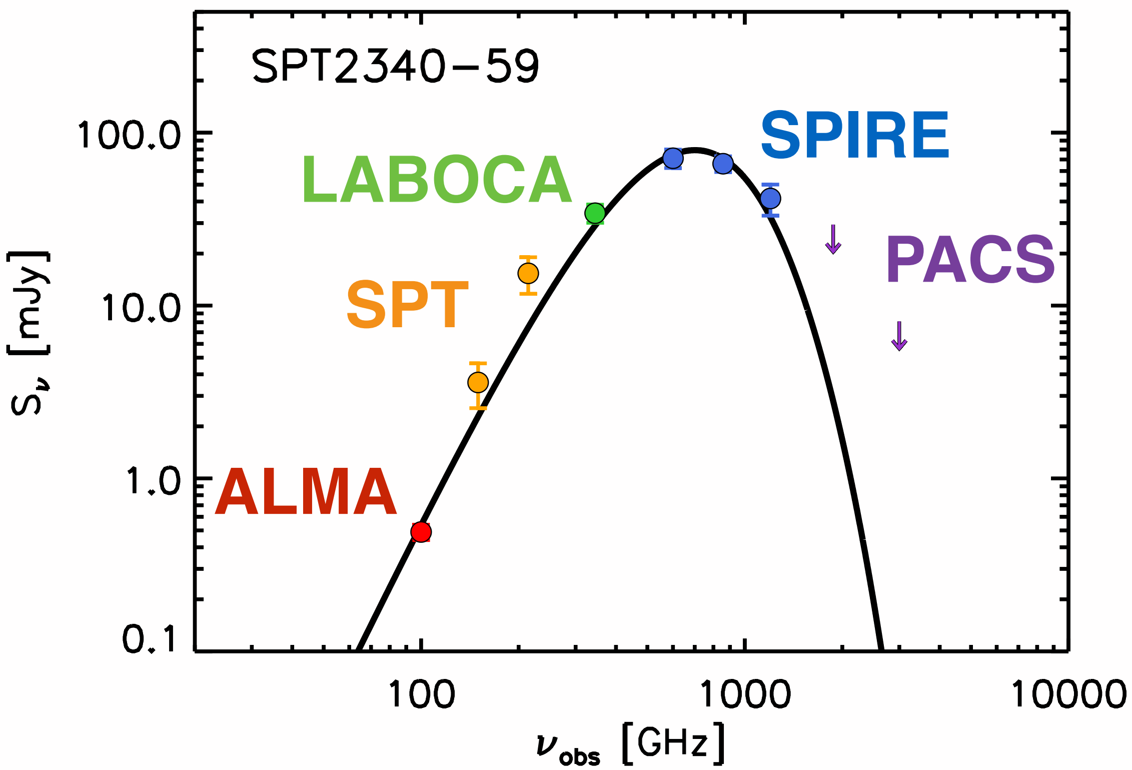
red = no line detected

ALMA spectra



Strandet et al. 2016

Solving single line ambiguities



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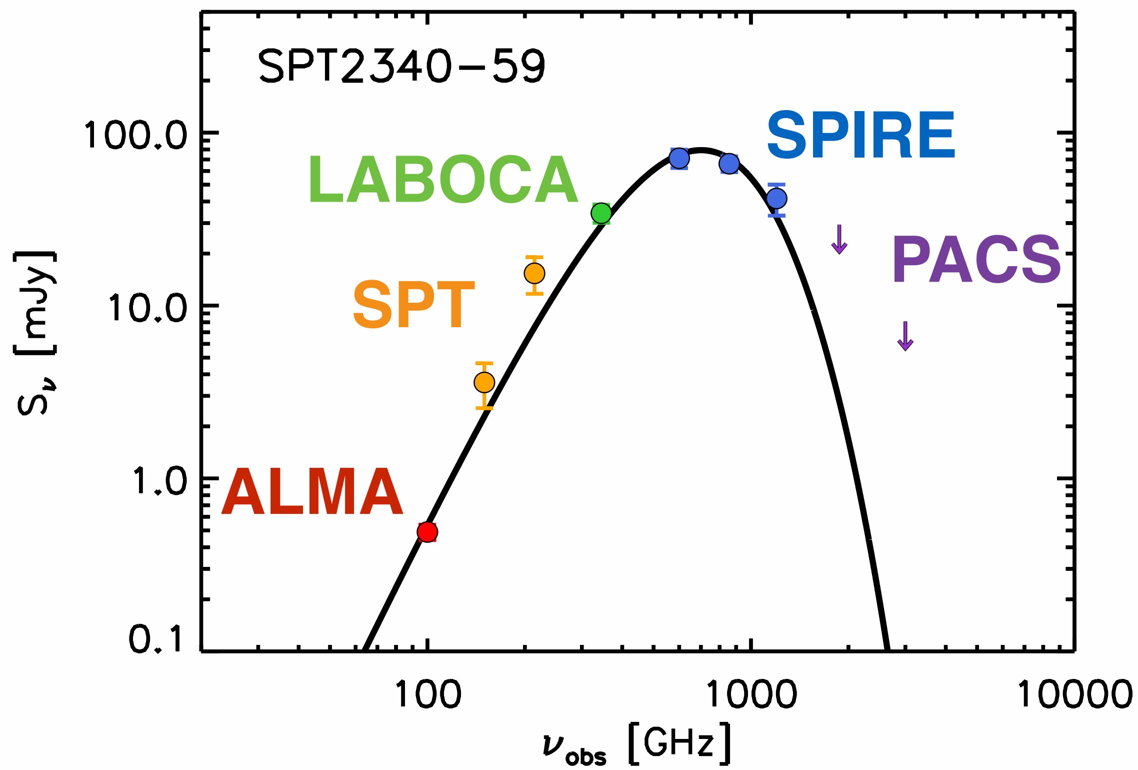

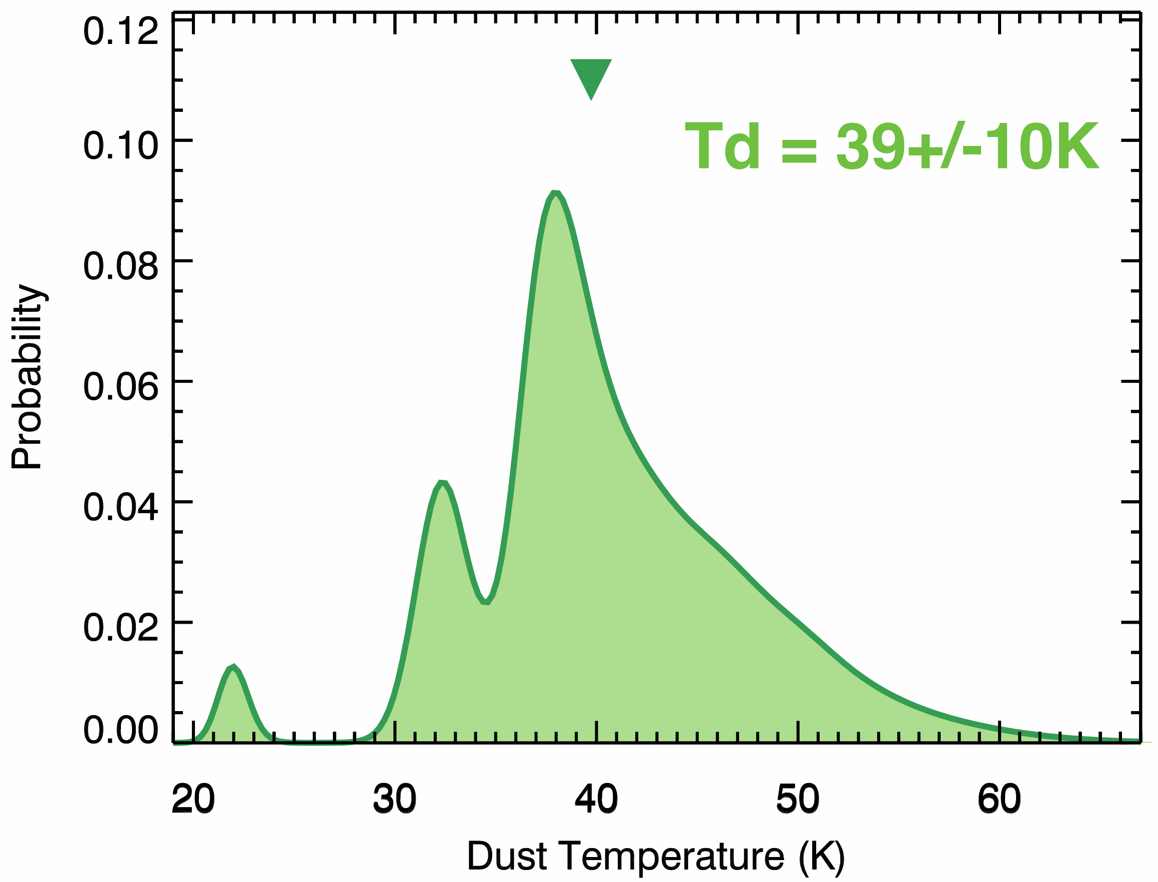

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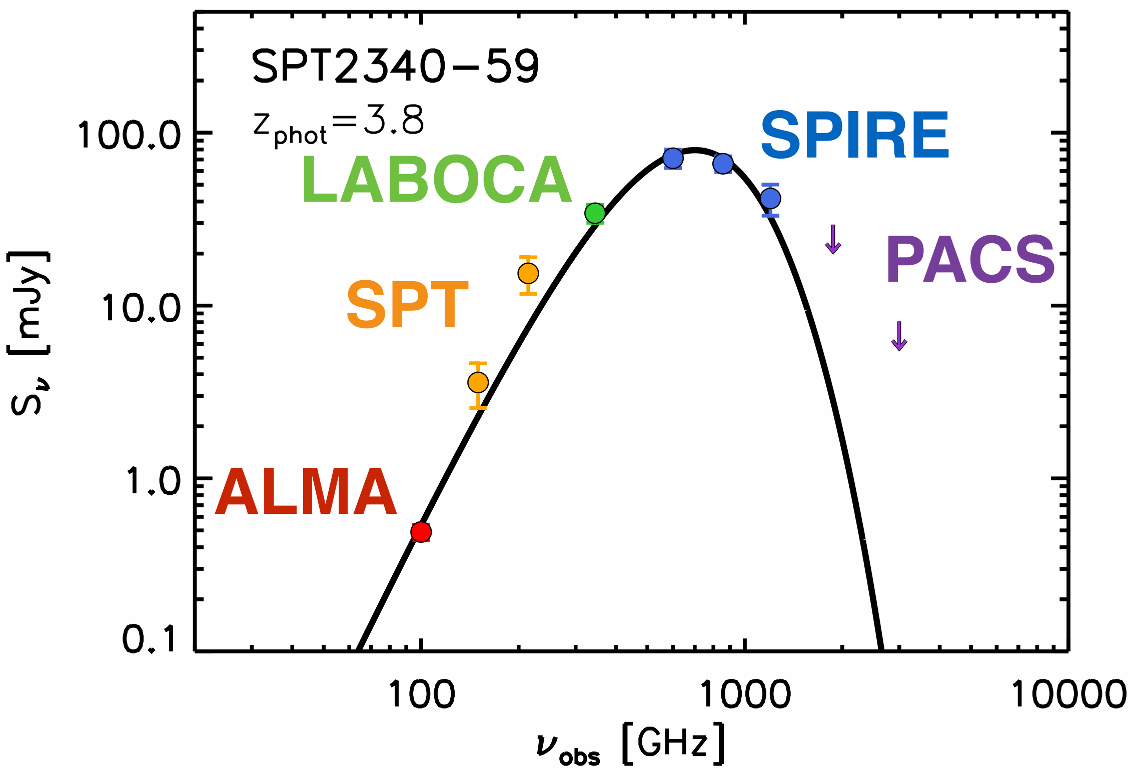

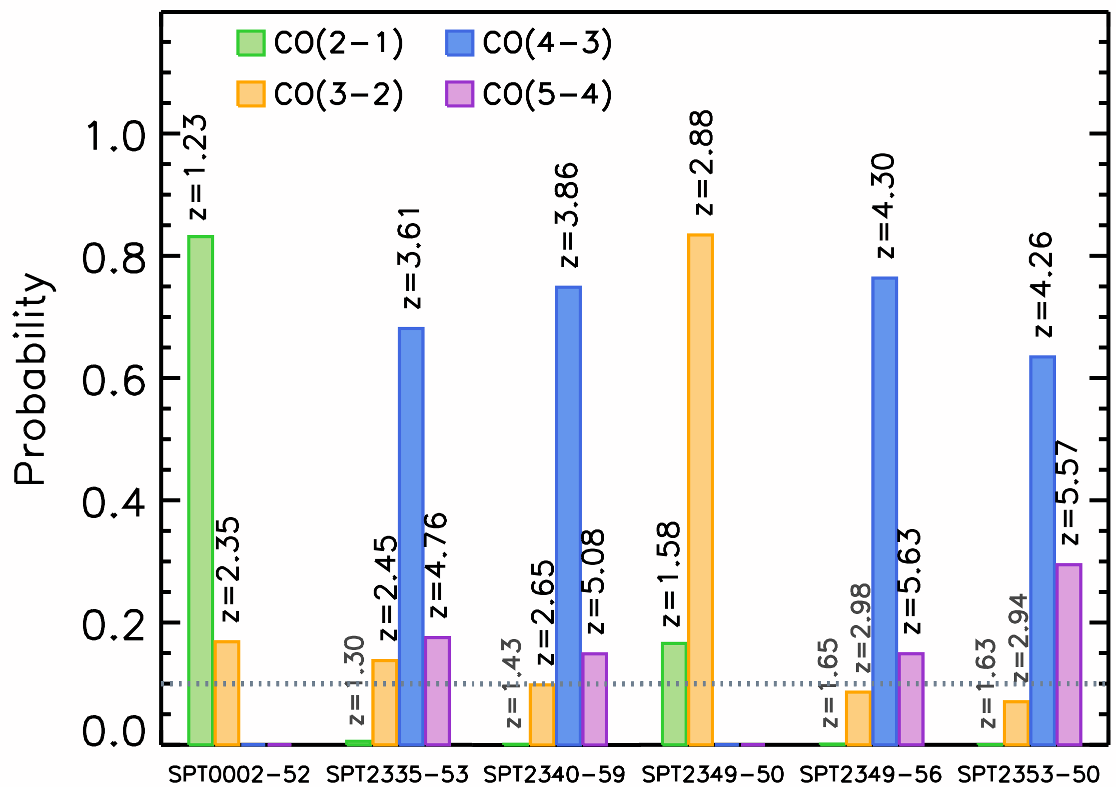

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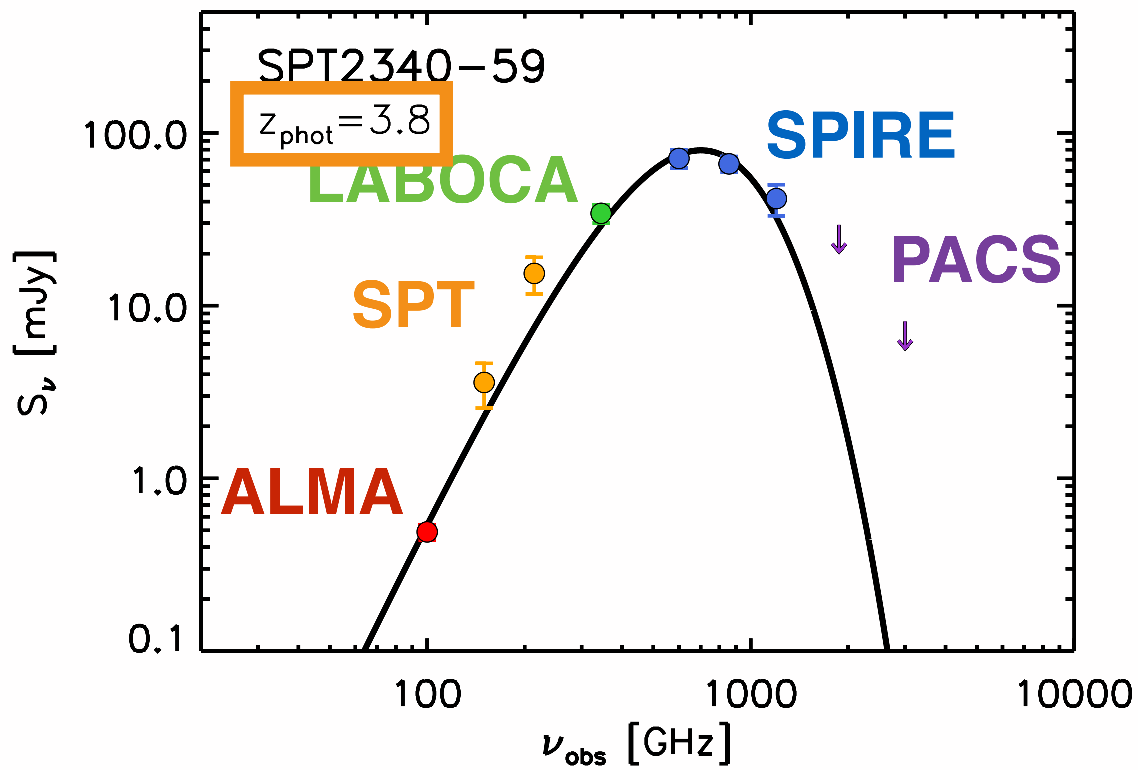

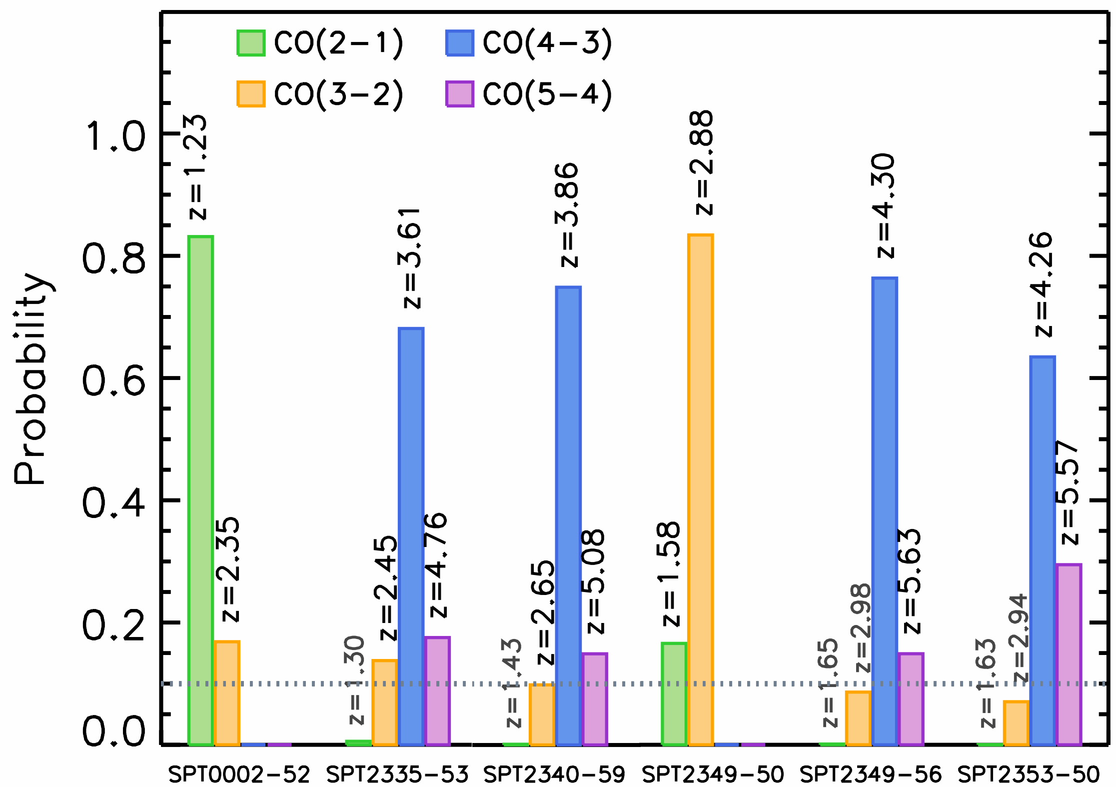

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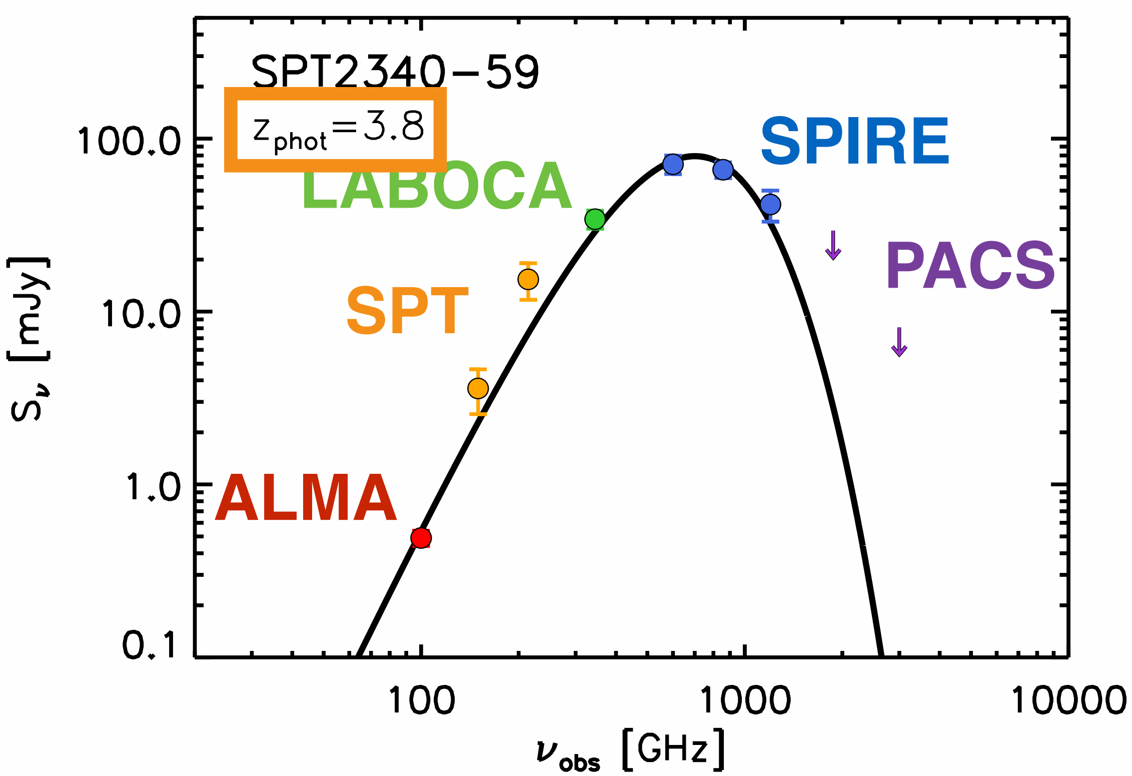
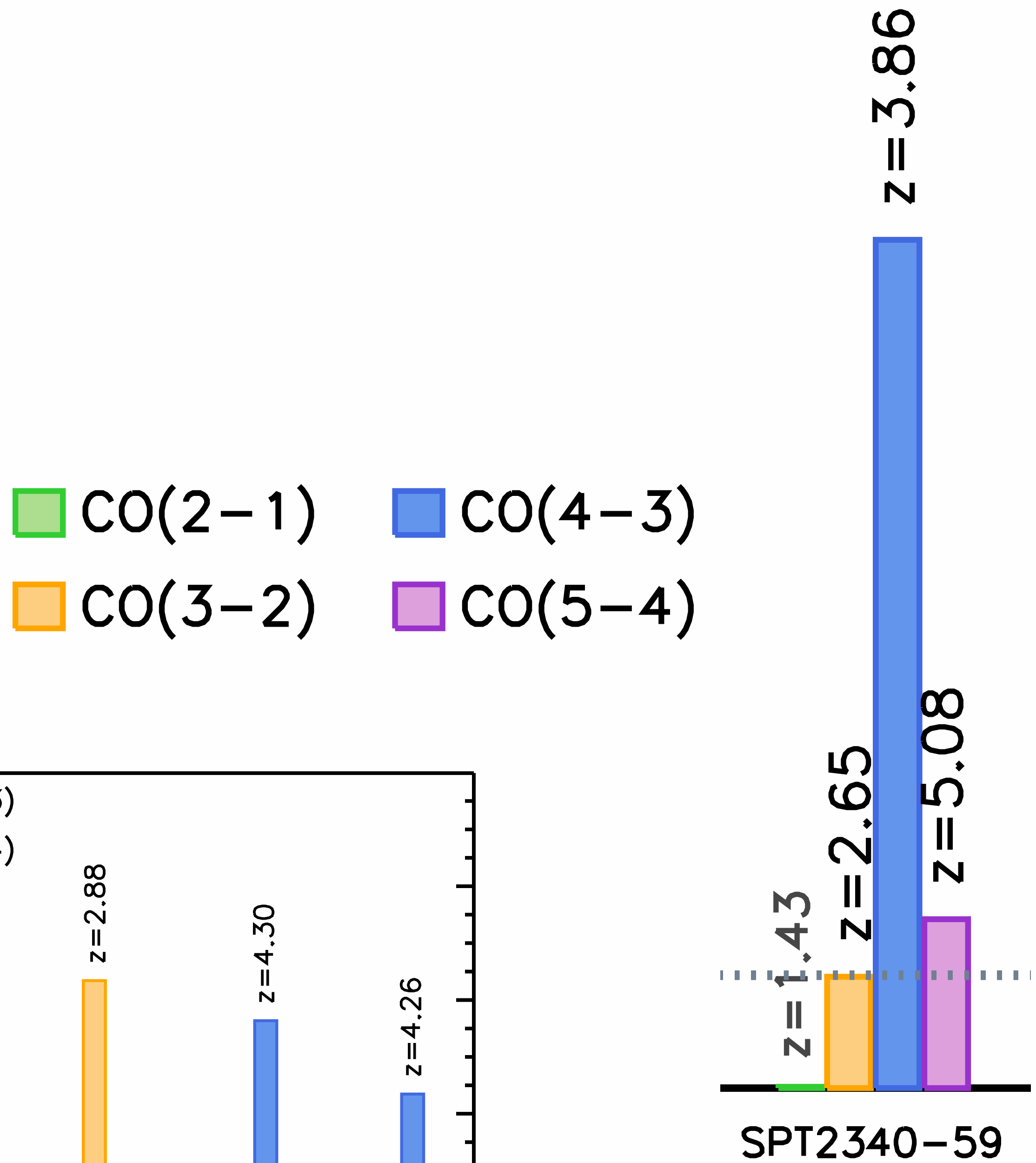
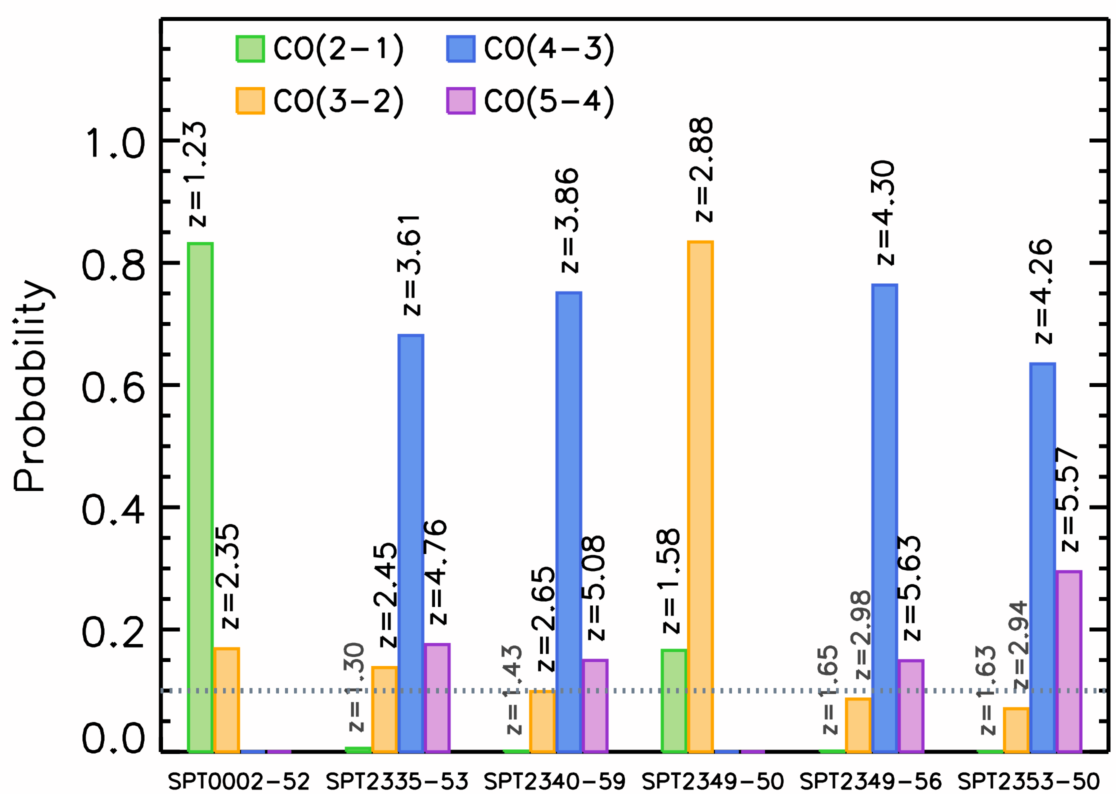
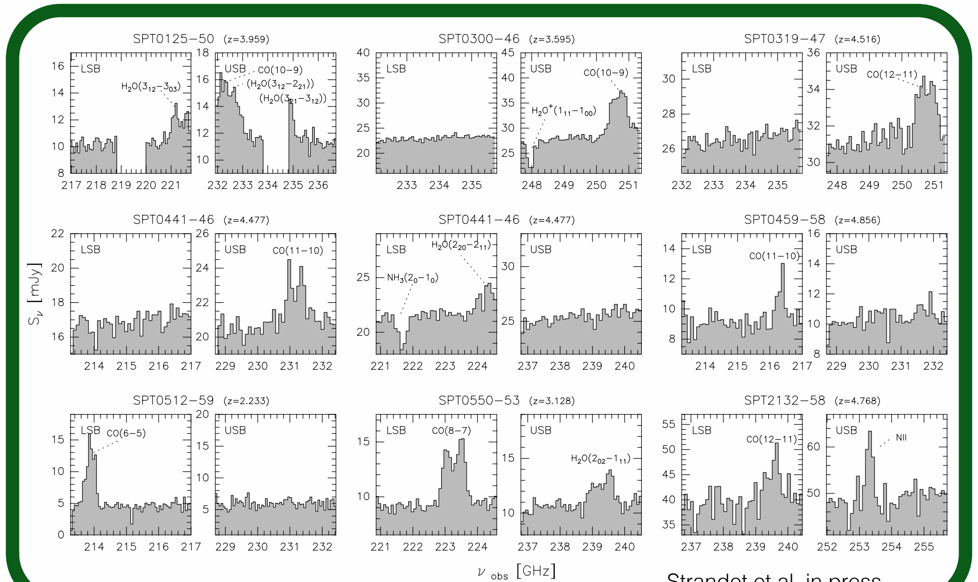






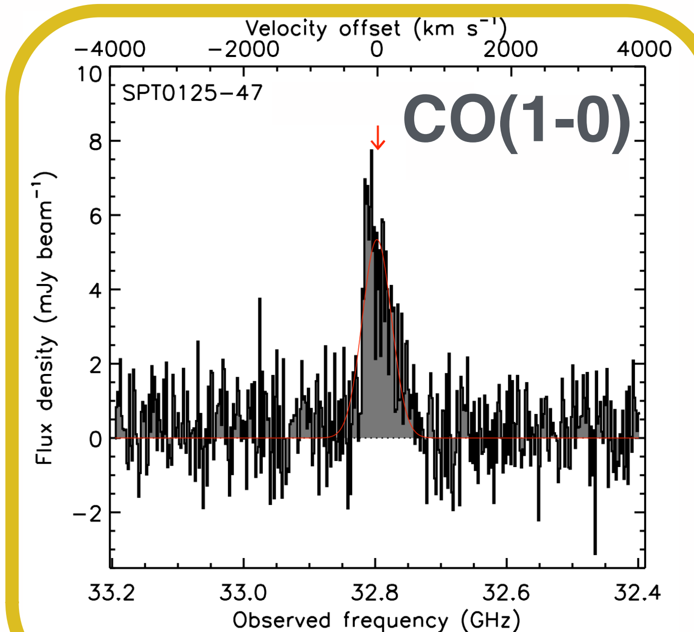
Redshift Confirmation

ALMA



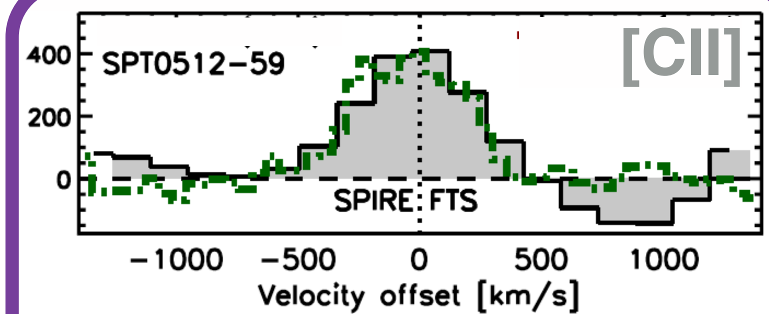
Strandet et al. in press

ATCA



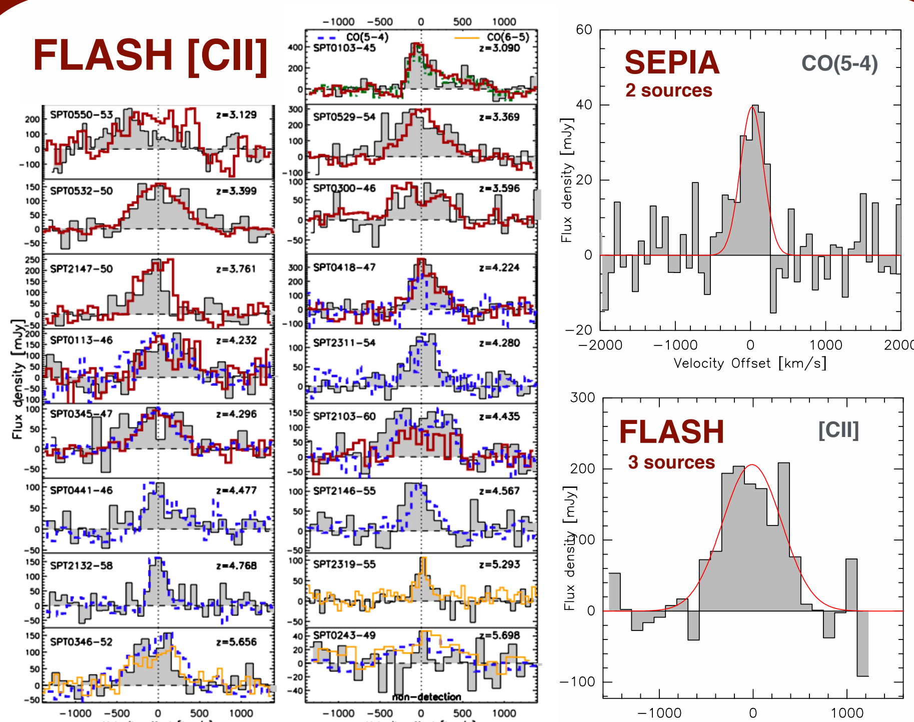
Weiss et al. 2013

SPIRE



Gullberg et al. 2015

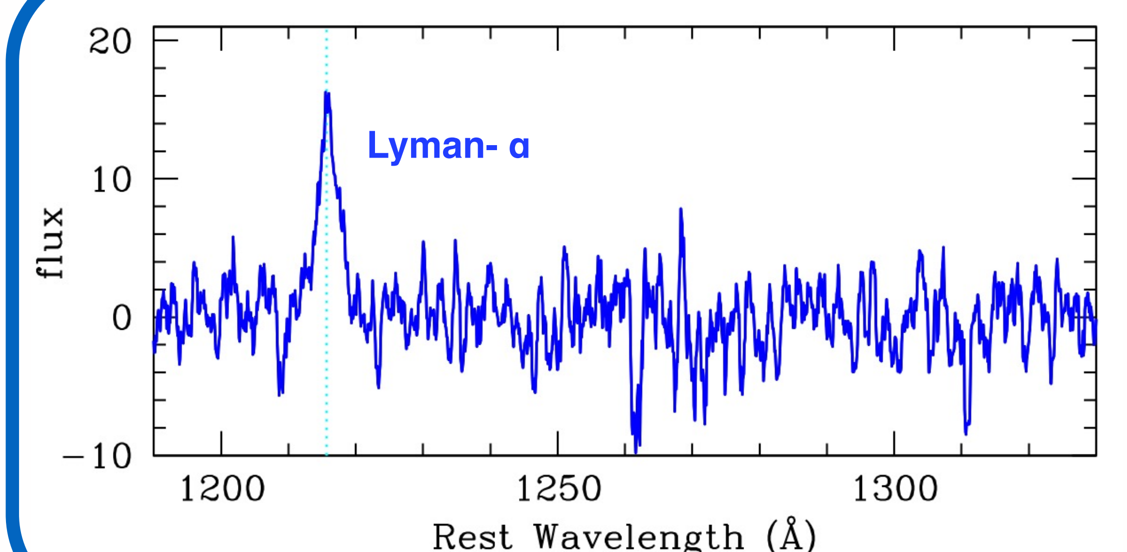
APEX



Gullberg et al. 2015

Strandet et al. 2016

VLT/X-shooter

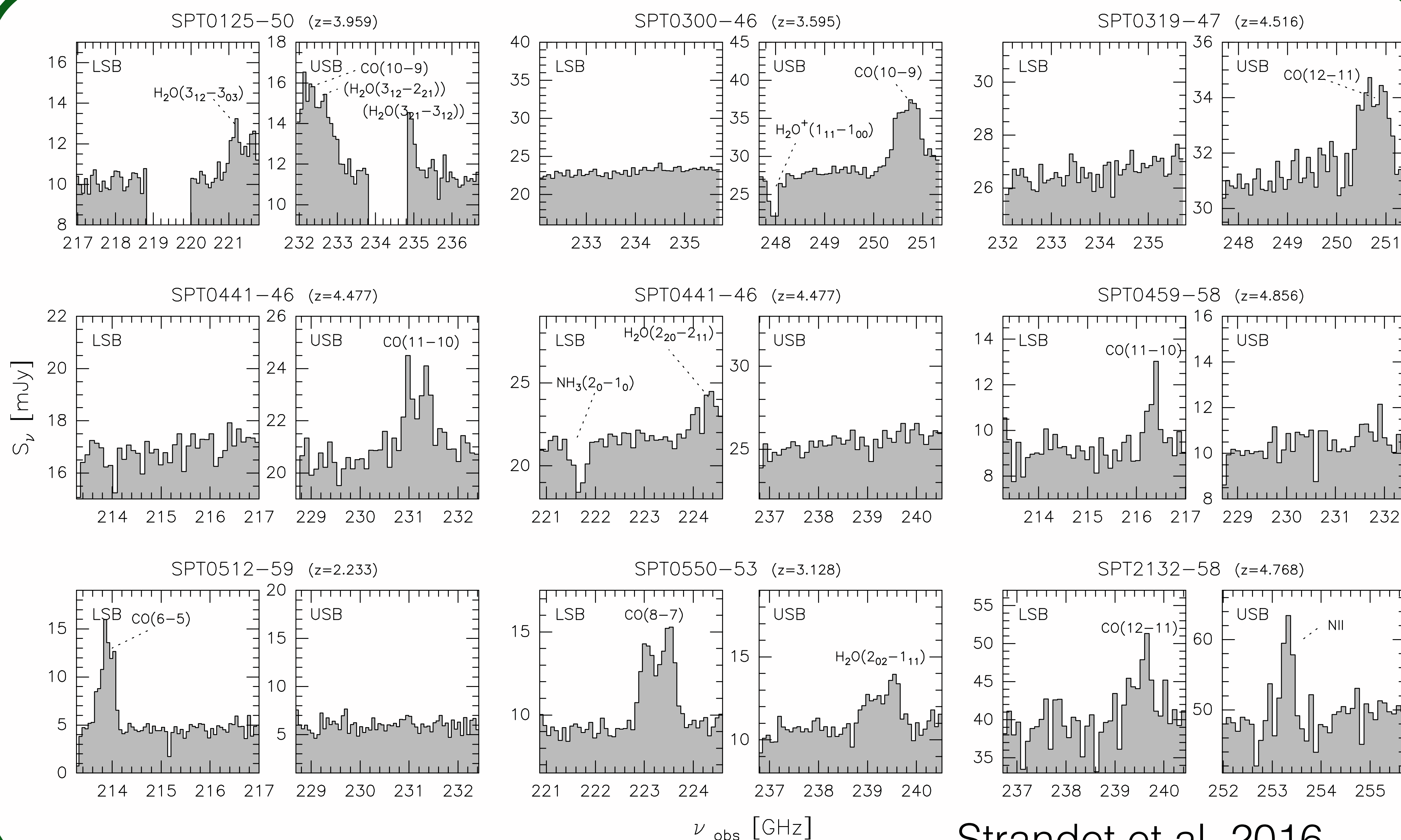


Strandet et al. in press

Redshift Confirmation

ALMA

ATCA



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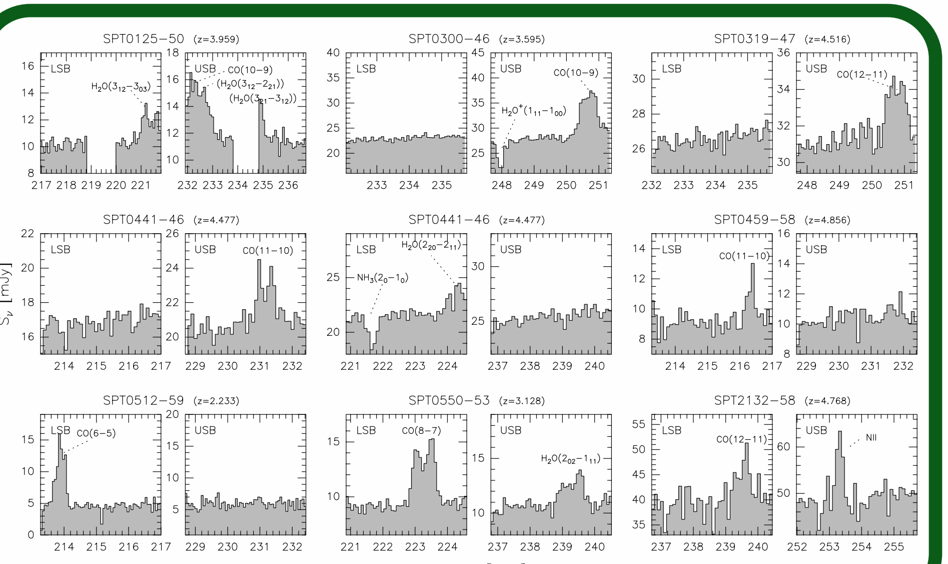

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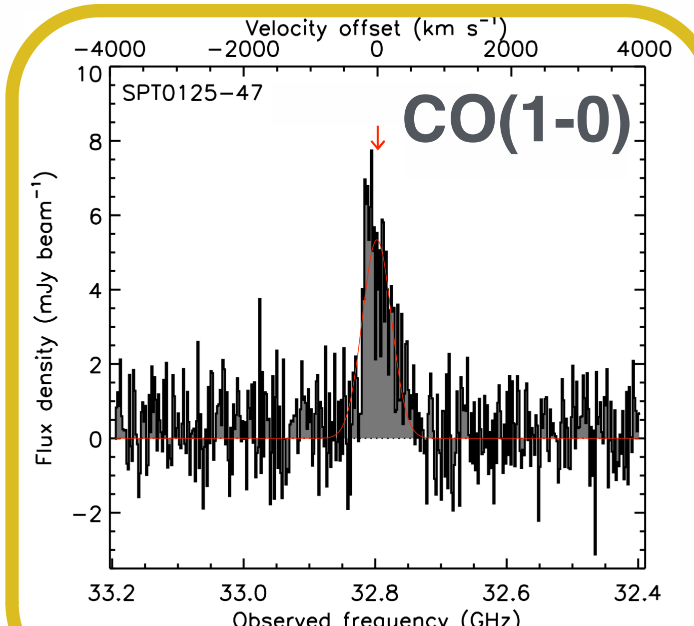

Weiss et al. 2013

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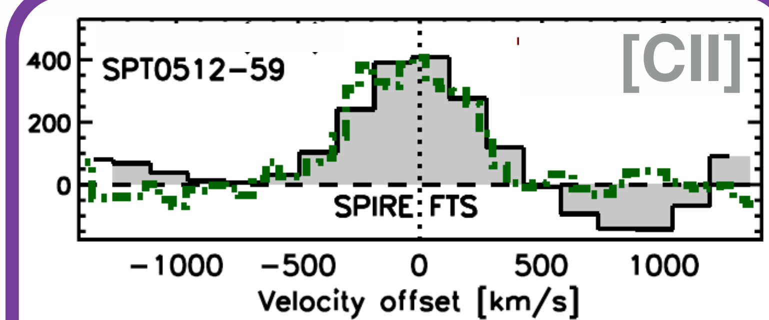

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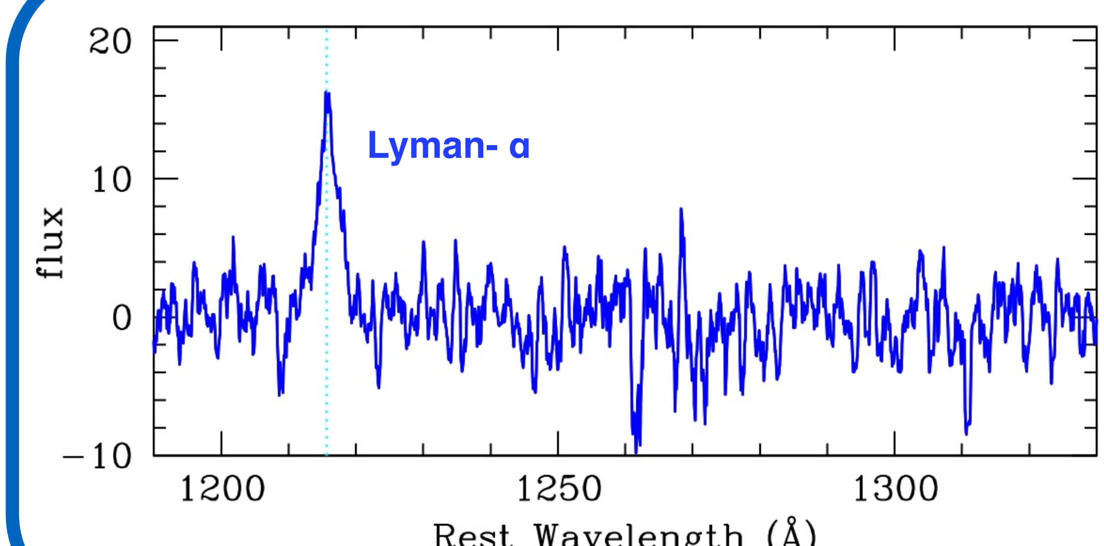

Strandet et al. in press

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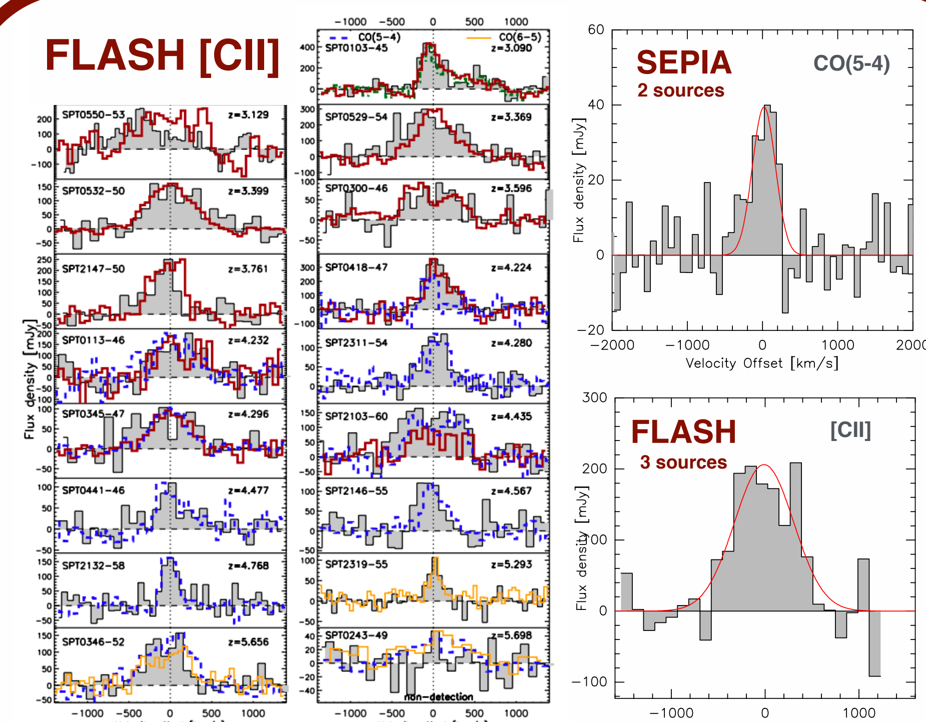

Gullberg et al. 2015

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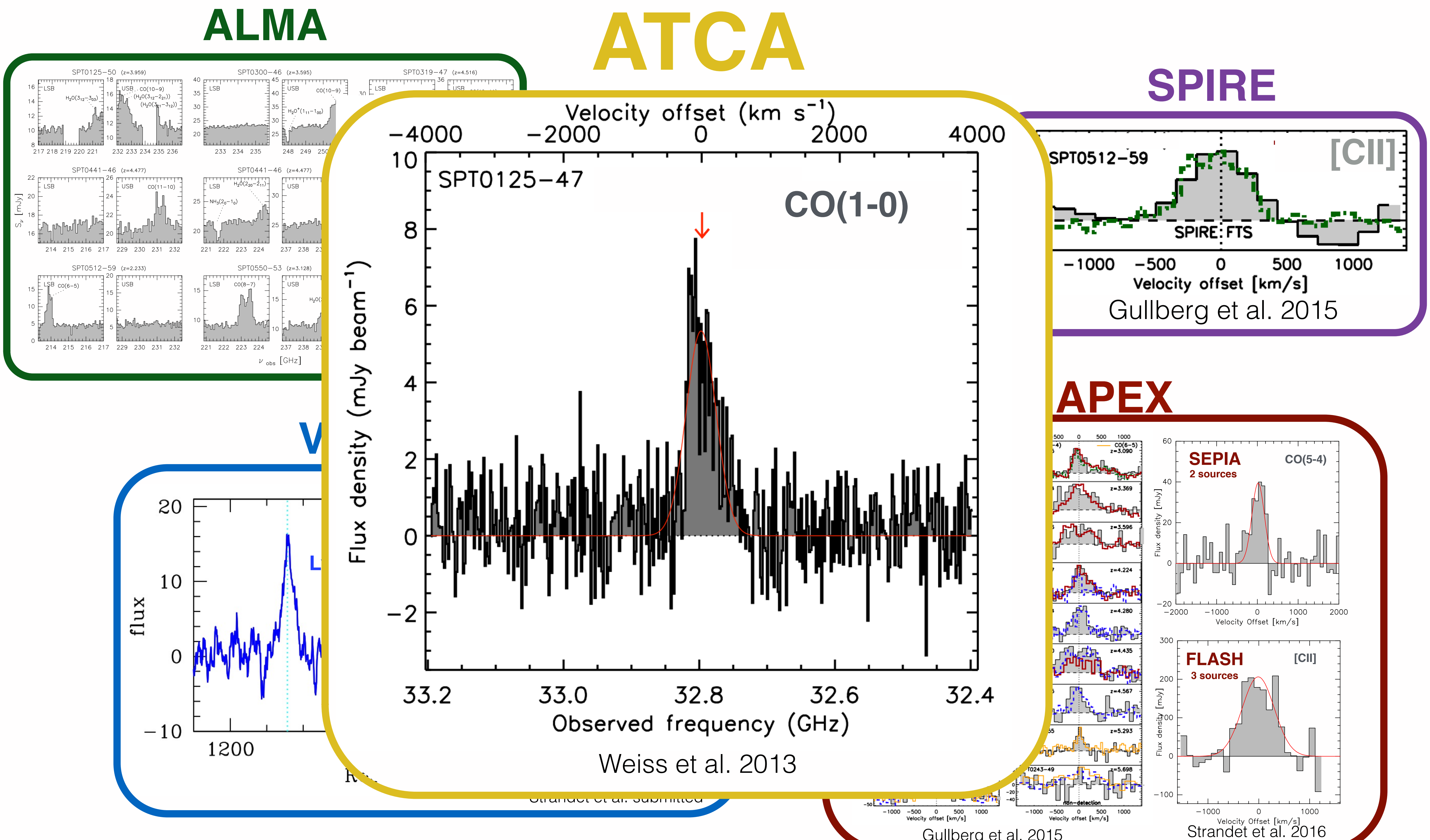

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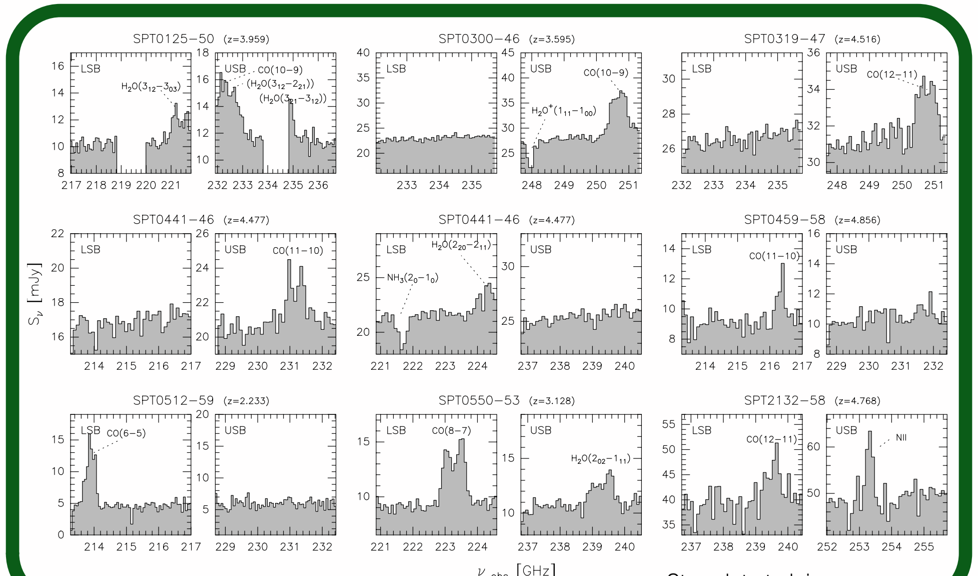
ALMA



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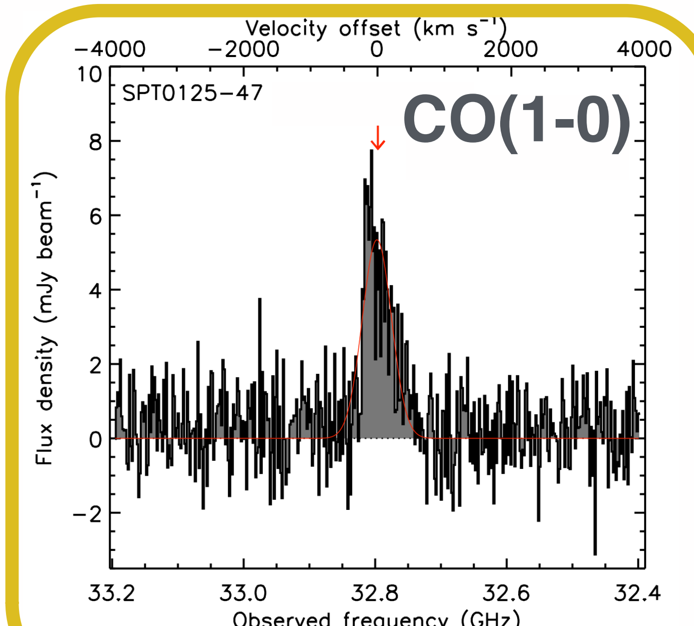

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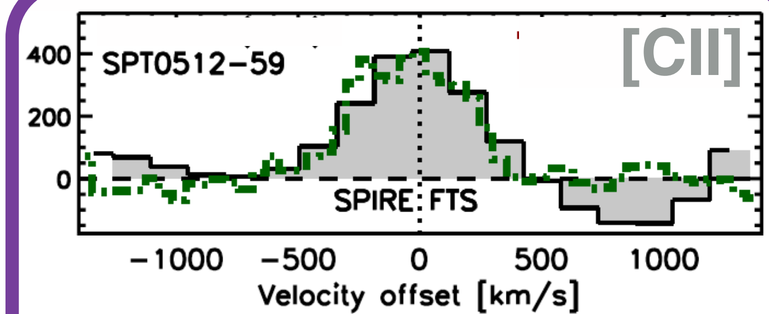

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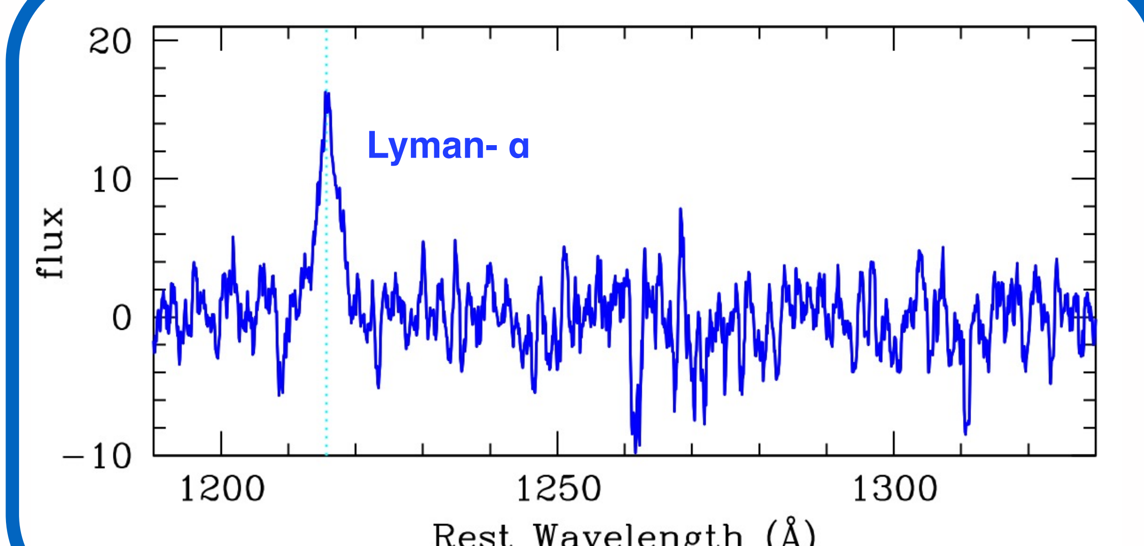

Strandet et al. in press

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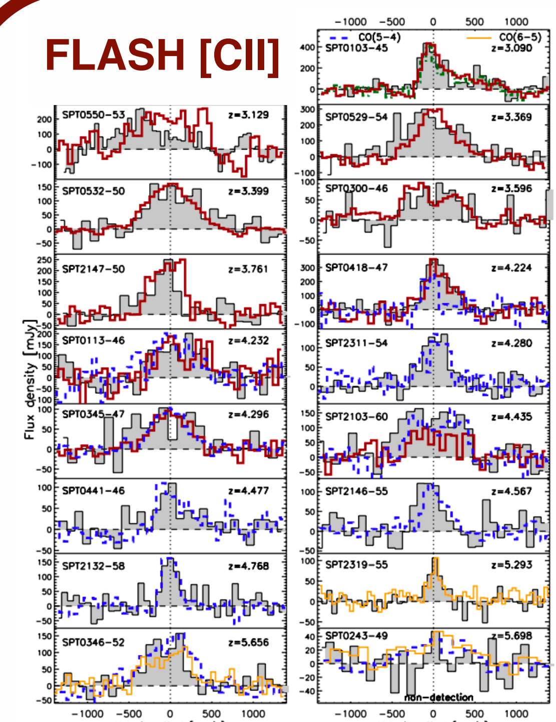
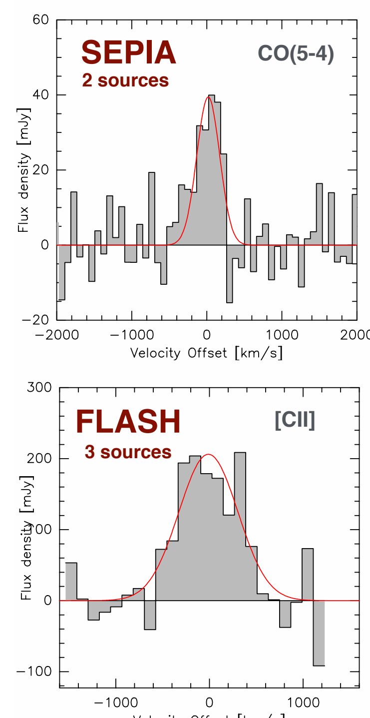
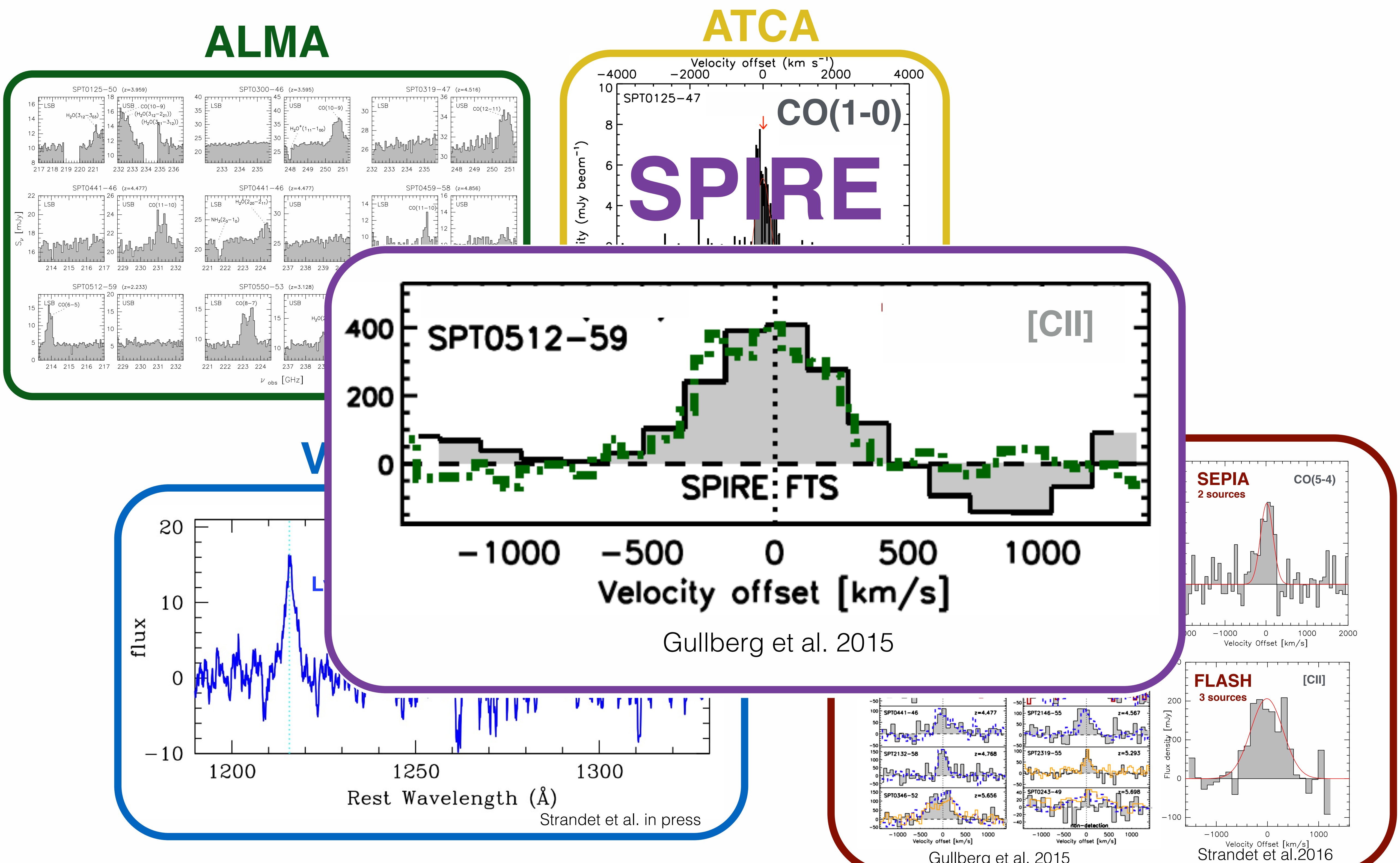


Gullberg et al. 2015



Strandet et al.2016

Redshift Confirmation



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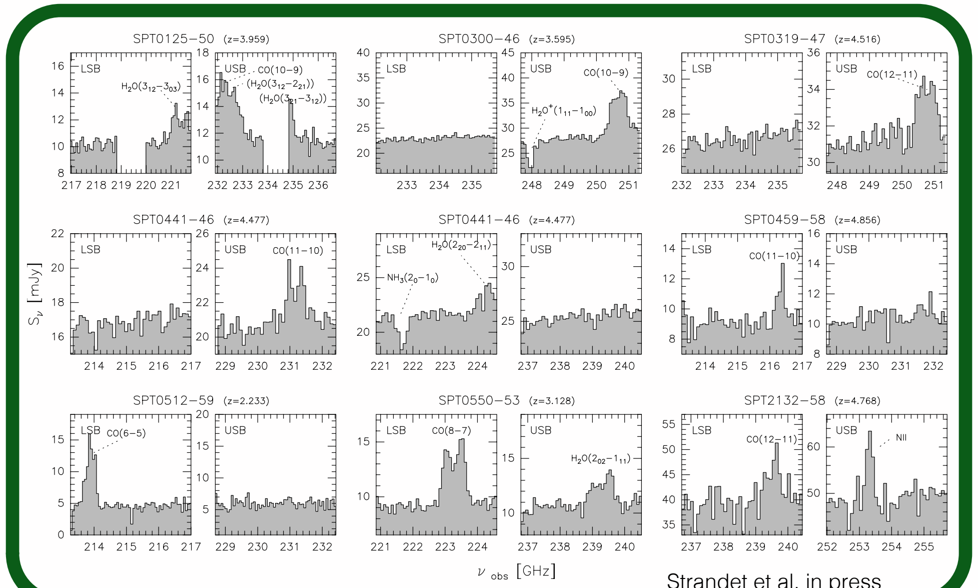

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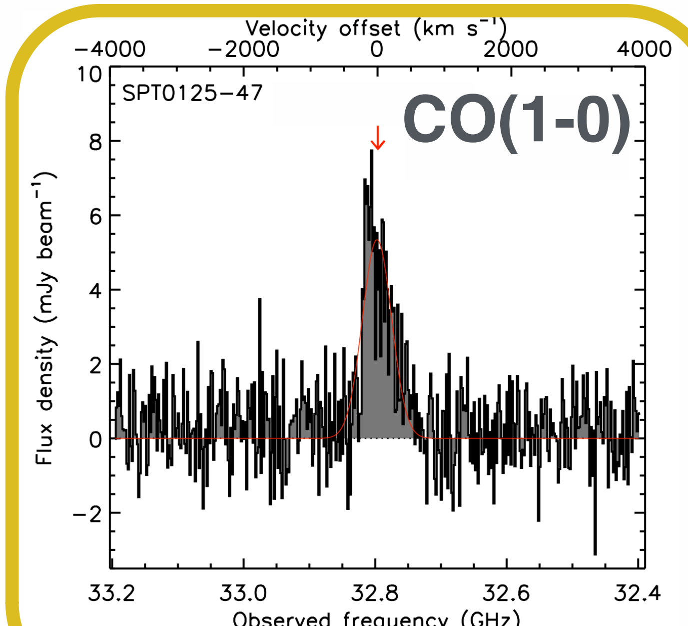

Weiss et al. 2013

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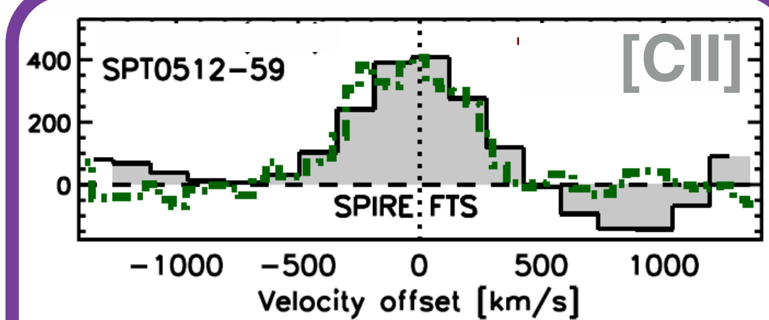

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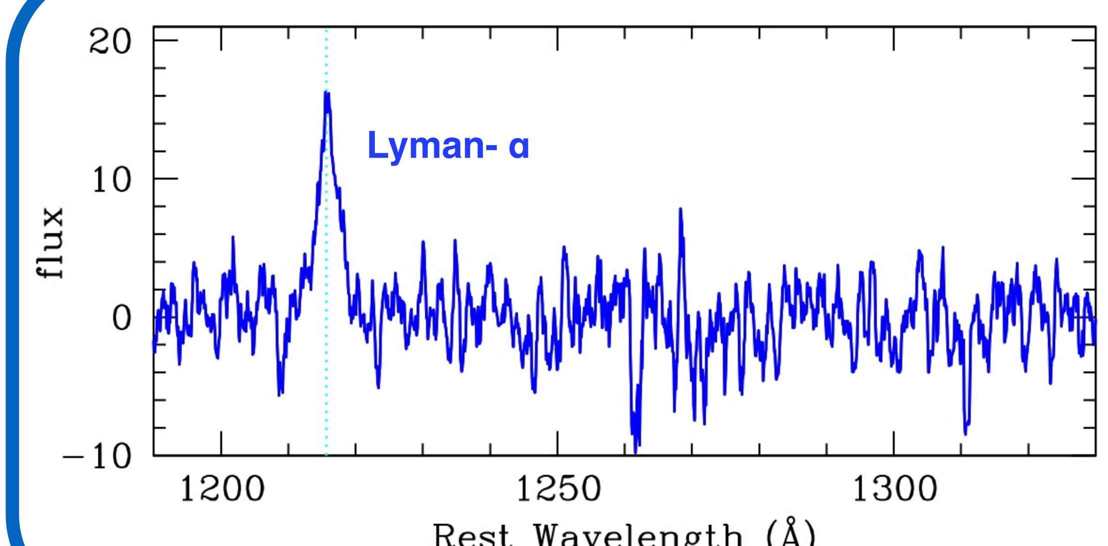

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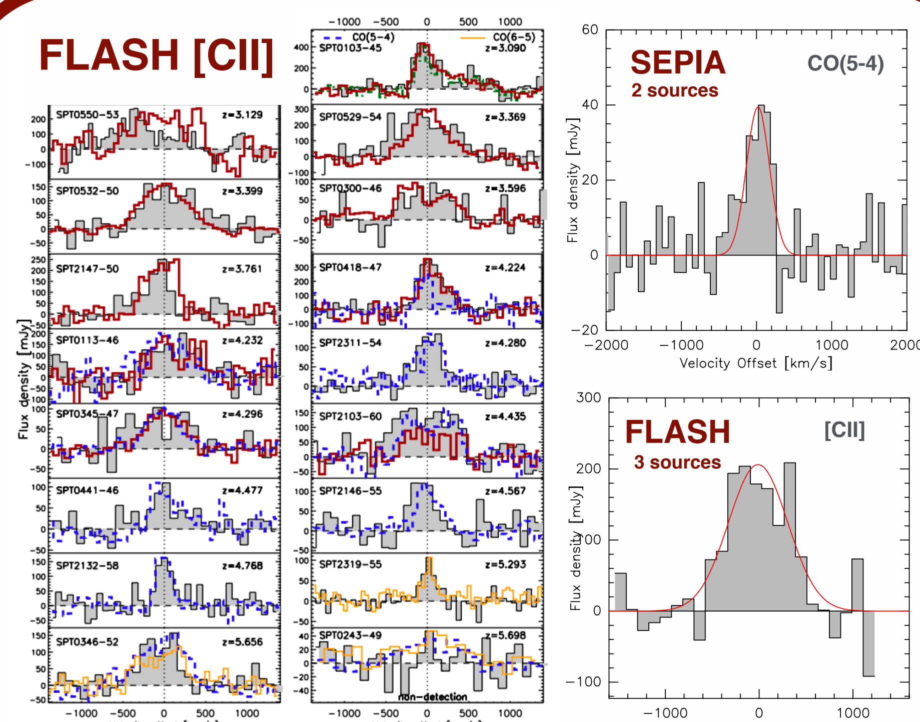

Gullberg et al. 2015

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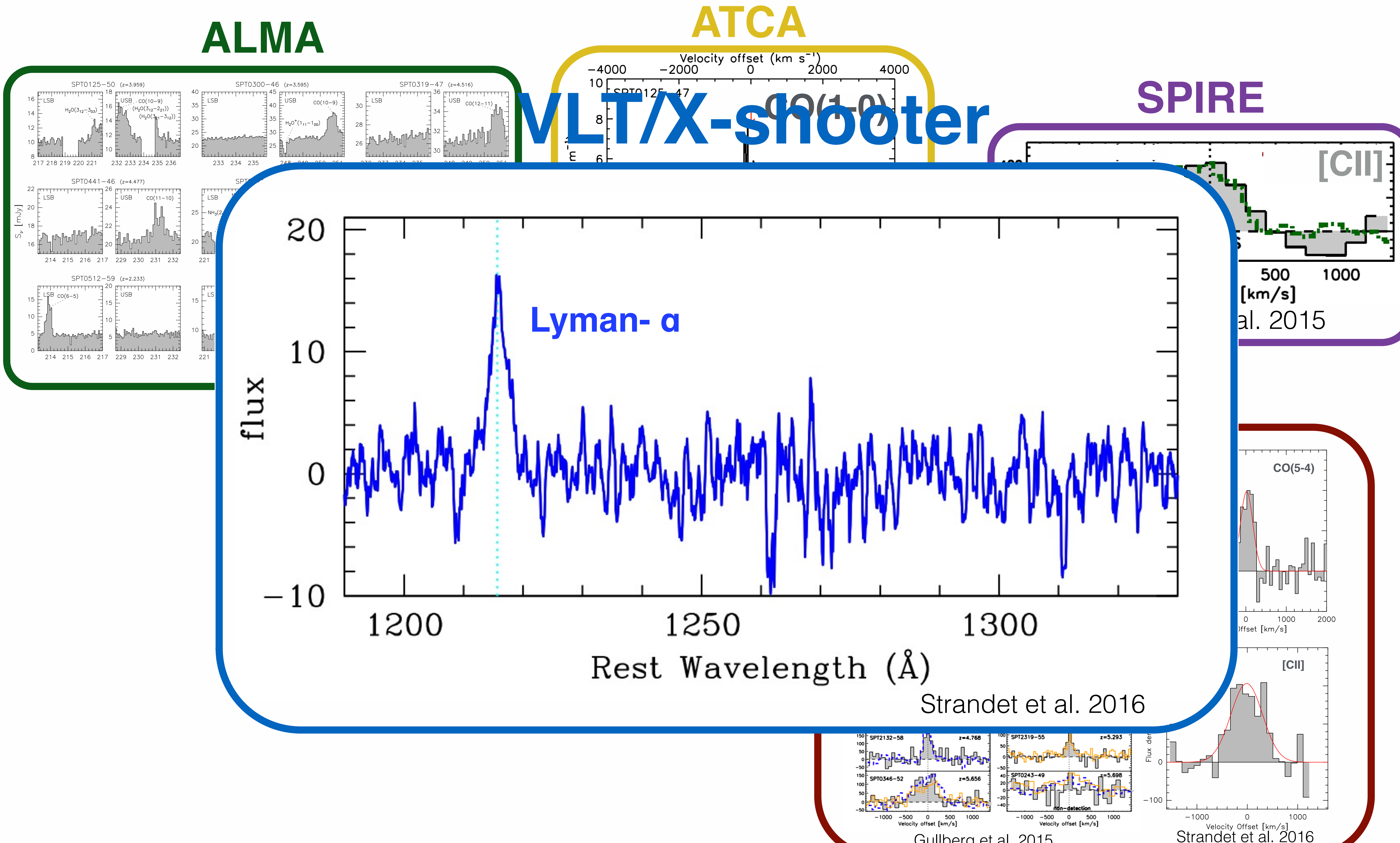
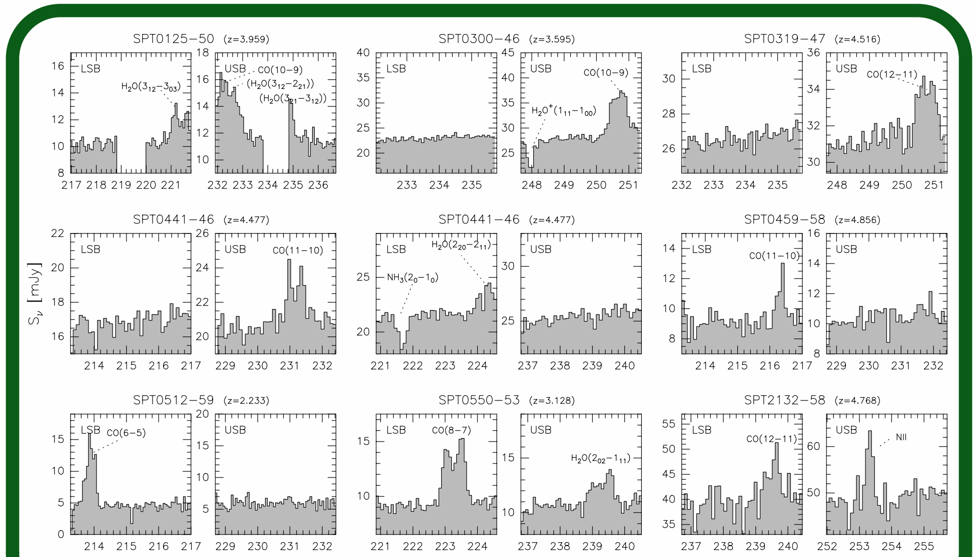


Redshift Confirmation

ALMA



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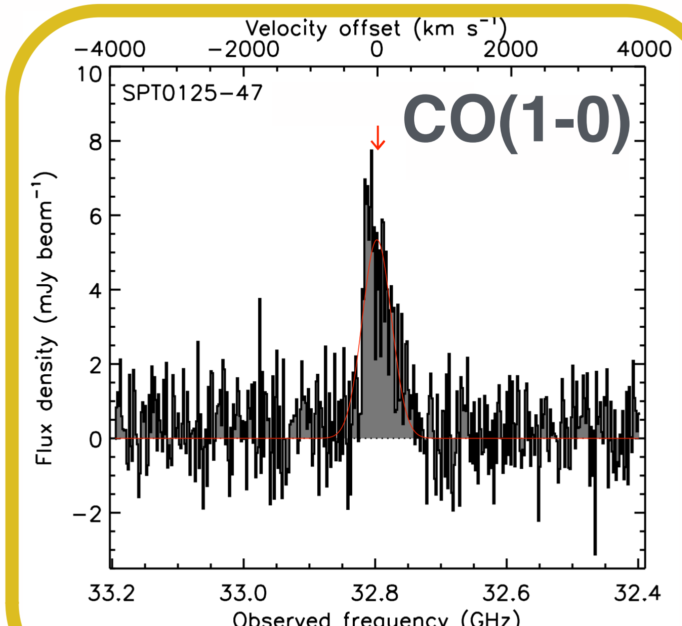

Weiss et al. 2013

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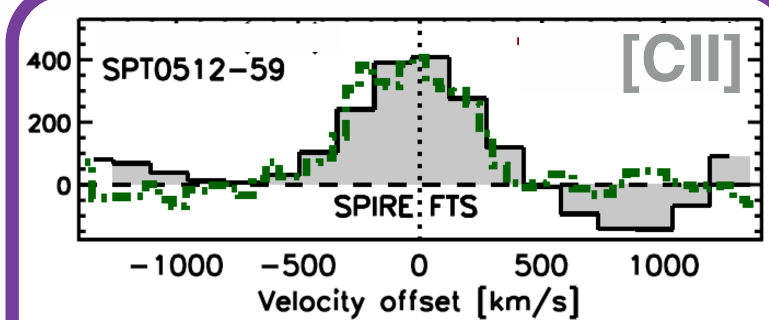

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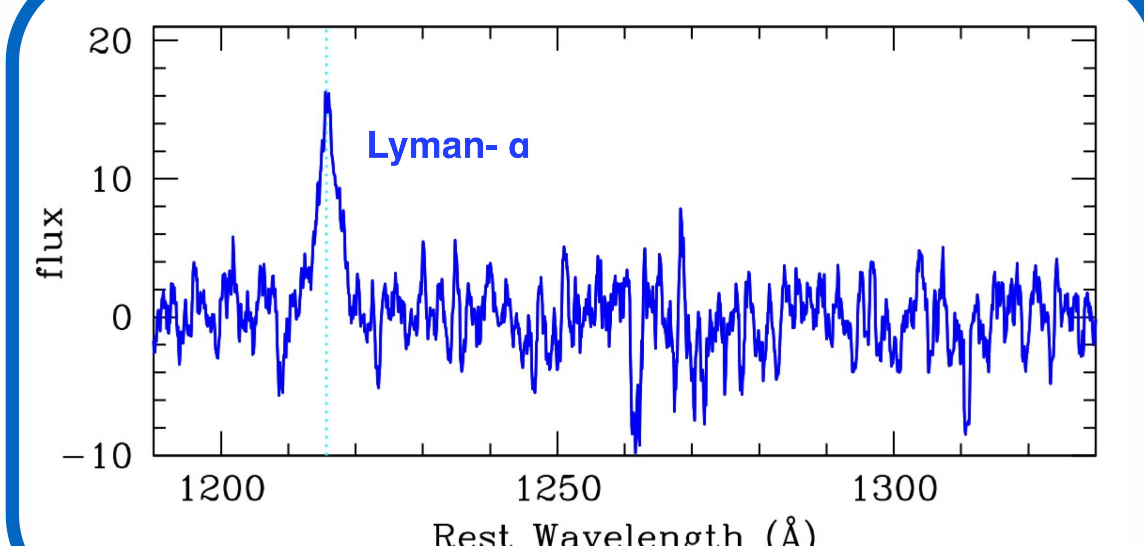

Strandet et al. in press

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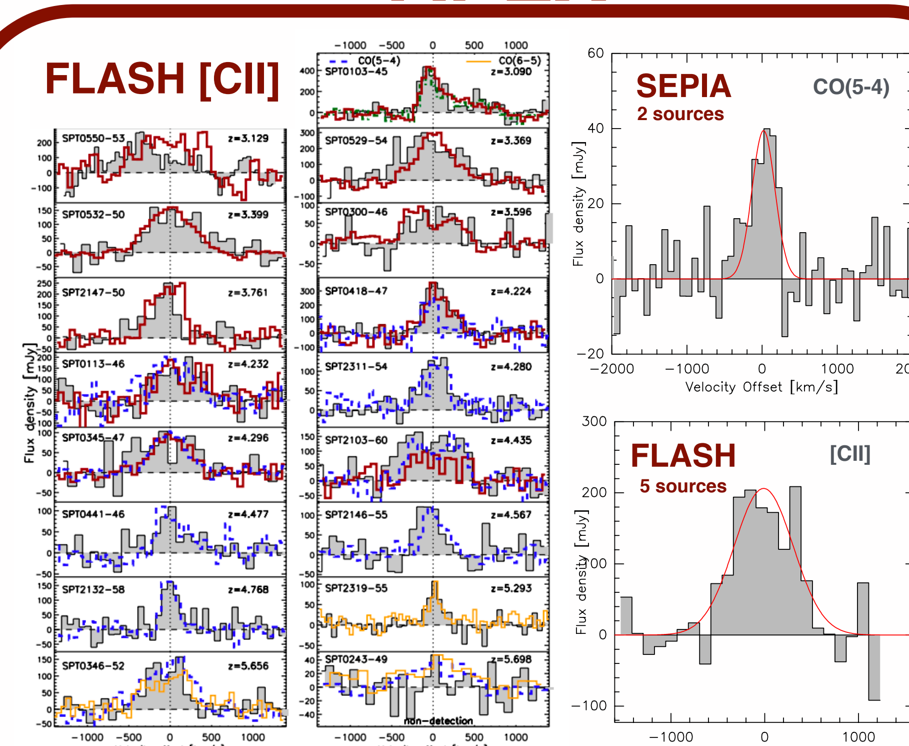

Gullberg et al. 2015

Strandet et al. 2016

Redshift Confirmation

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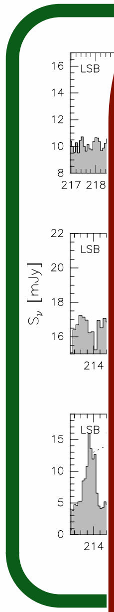

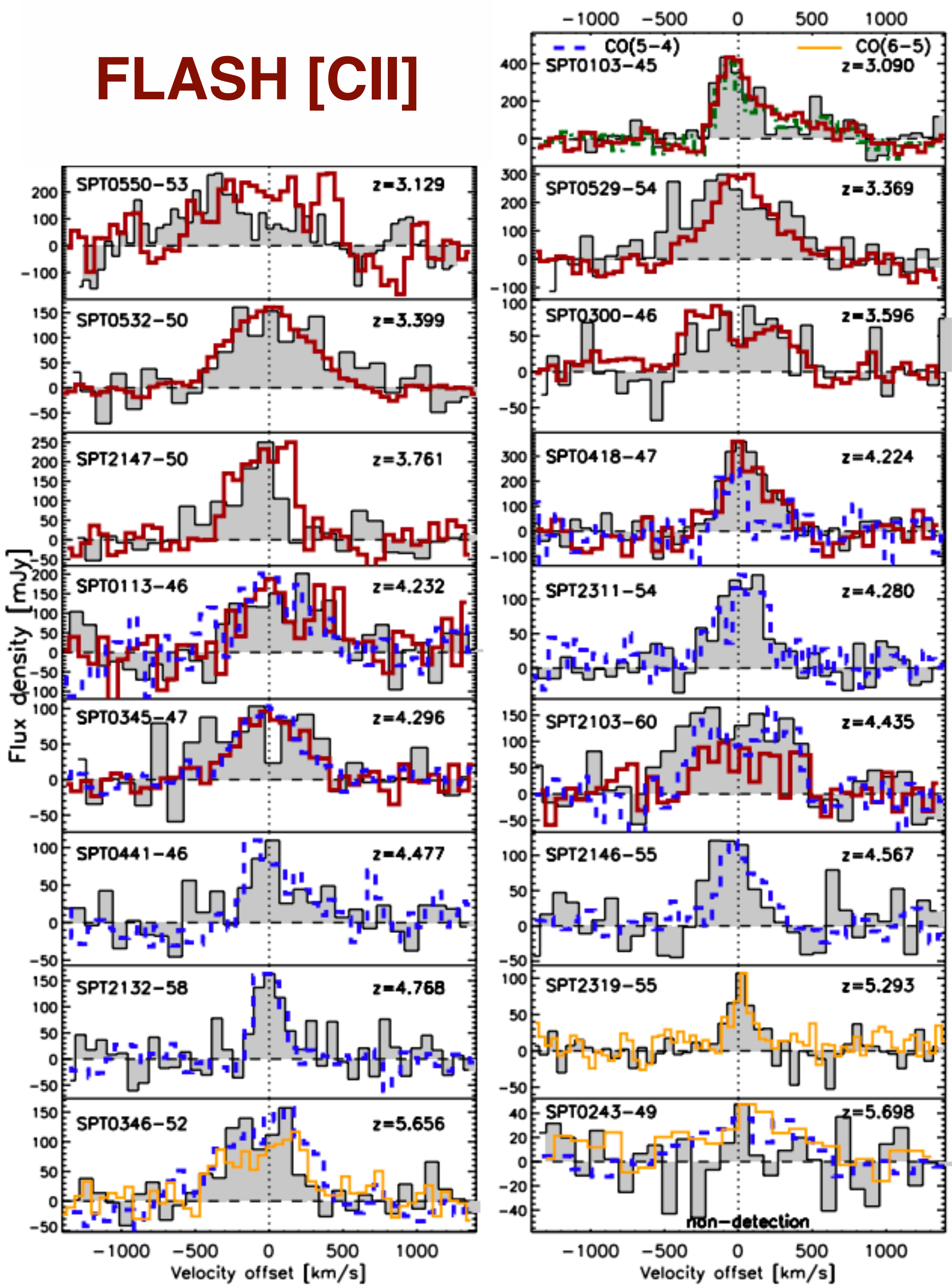

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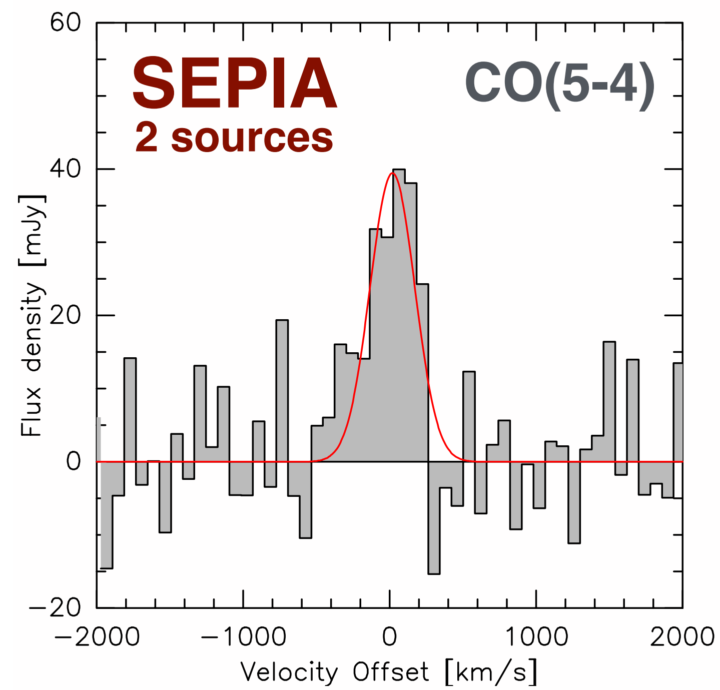

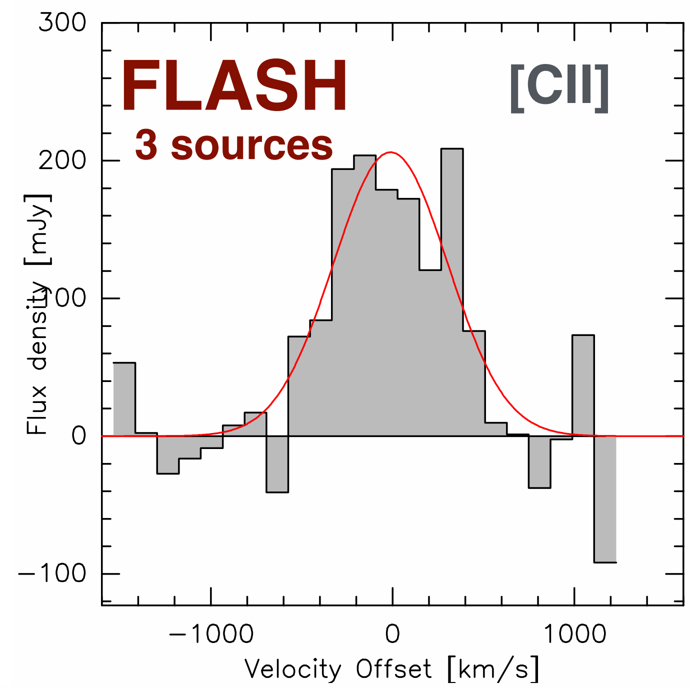

Strandet et al. 2016

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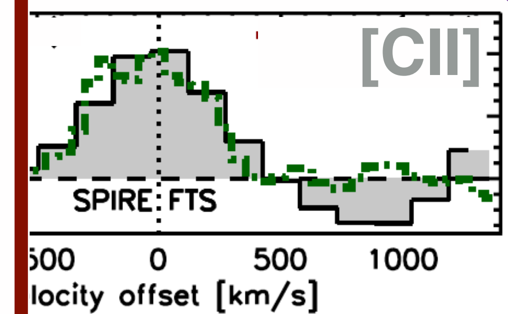

lberg et al. 2015

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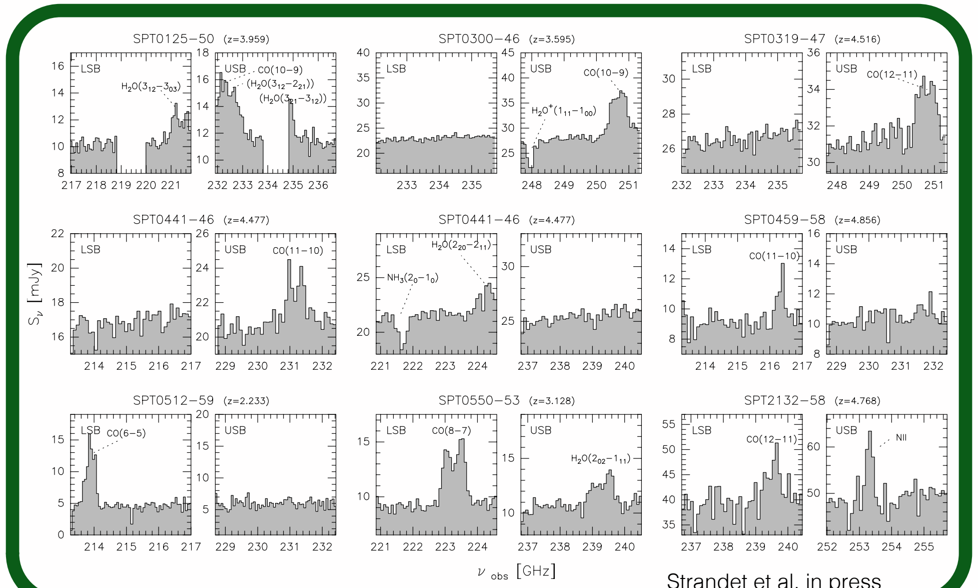
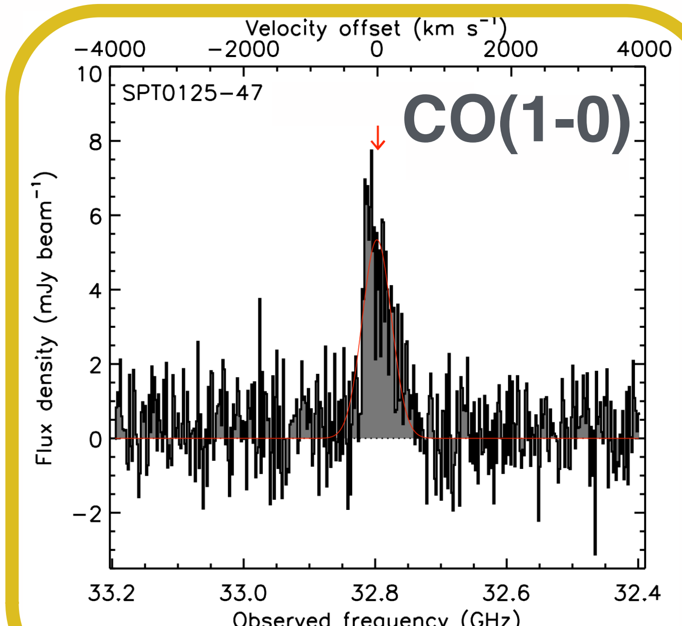


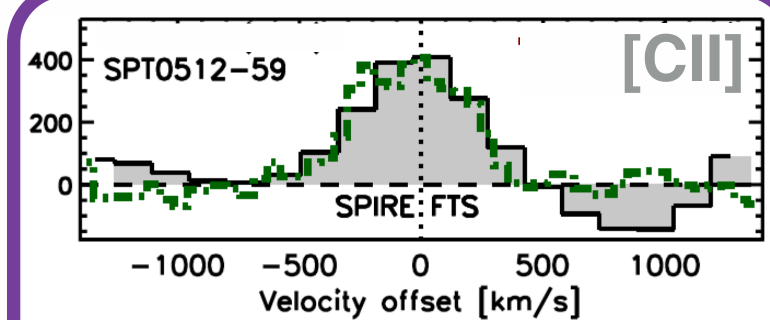
Strandet et al. in press

ATCA



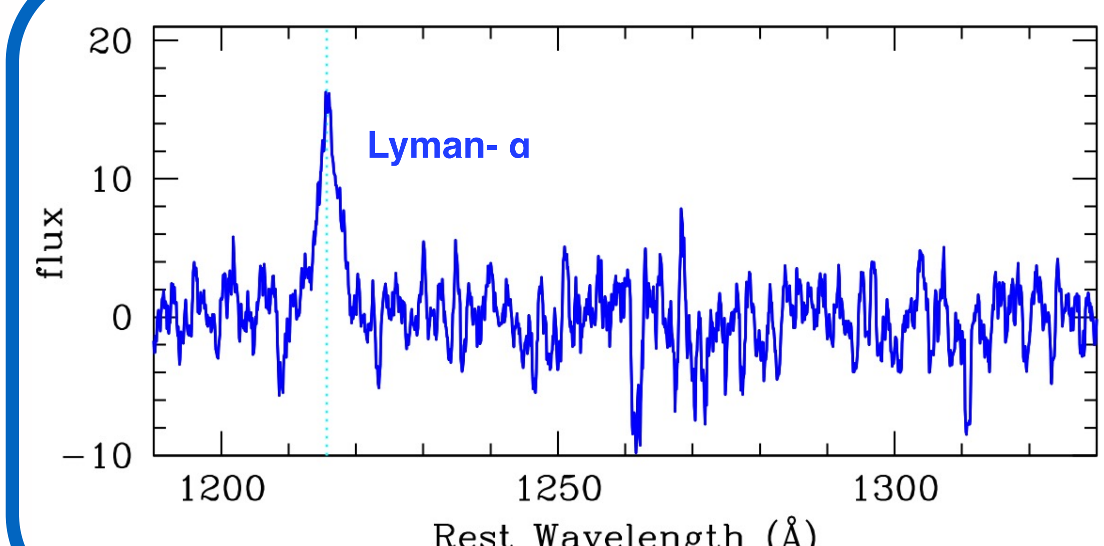
Weiss et al. 2013

SPIRE



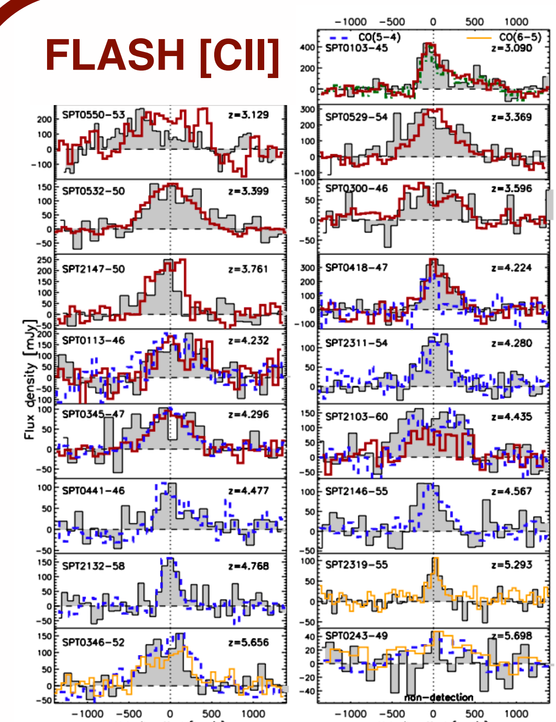
Gullberg et al. 2015

VLT/X-shooter

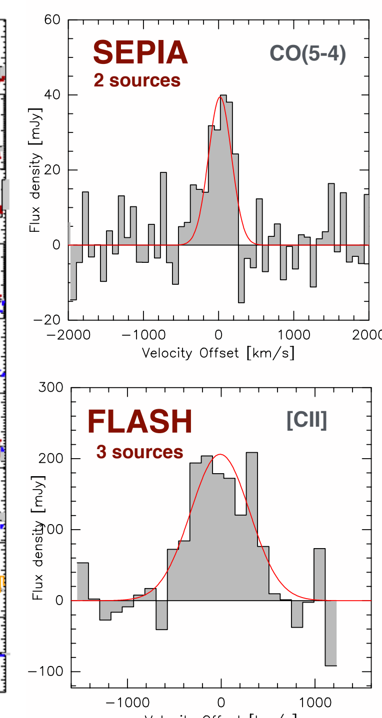


Strandet et al. in press

APEX

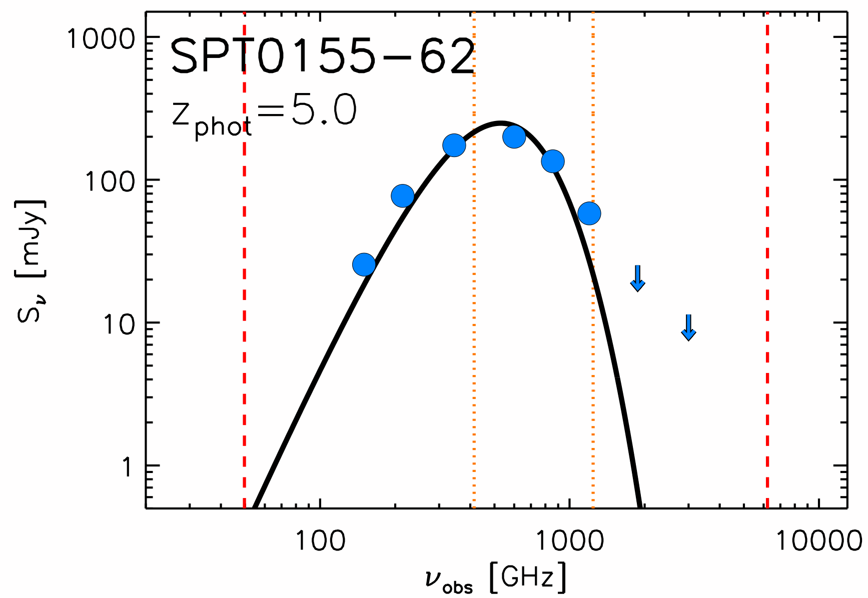


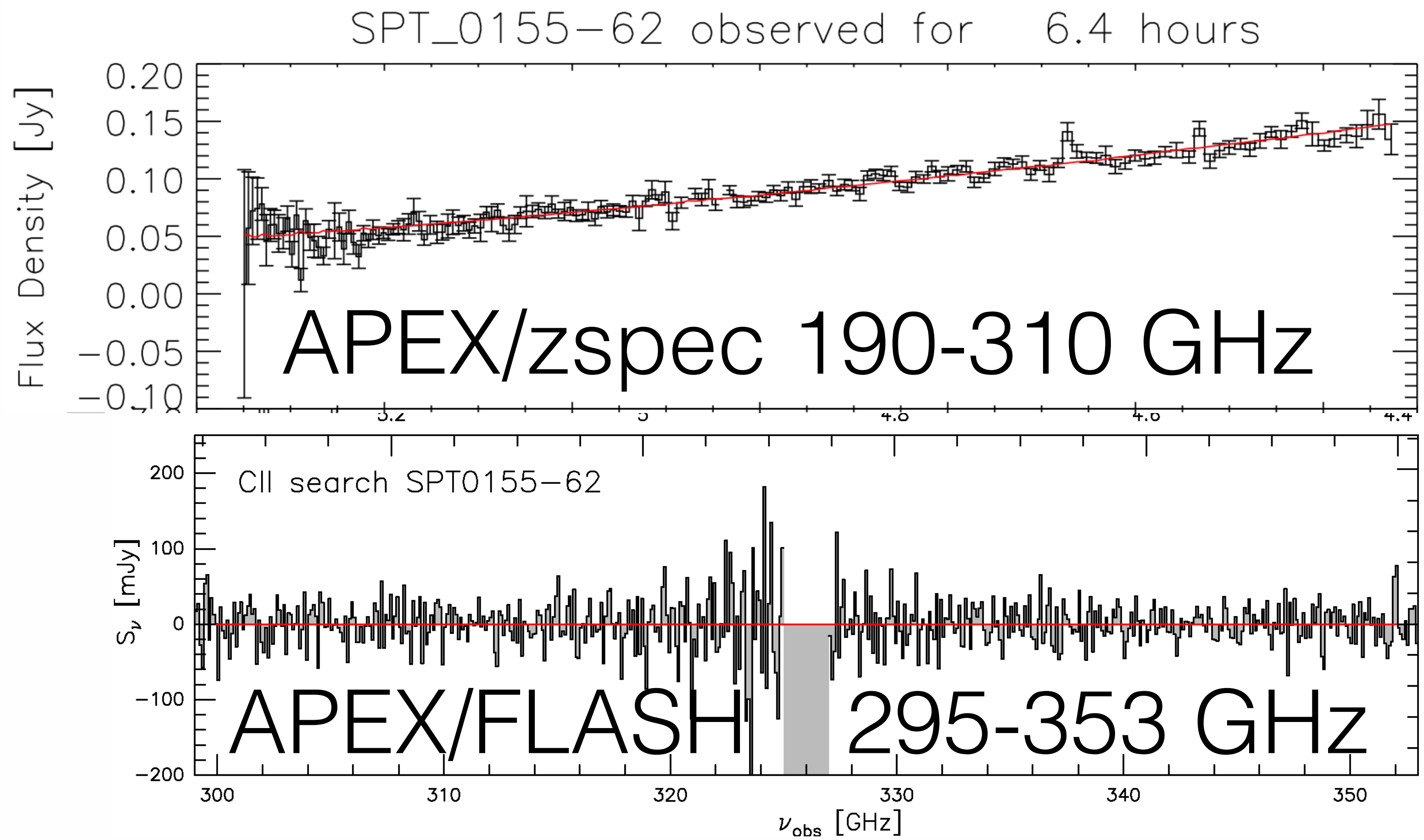
Gullberg et al. 2015



Strandet et al. 2016

Especially exciting sources

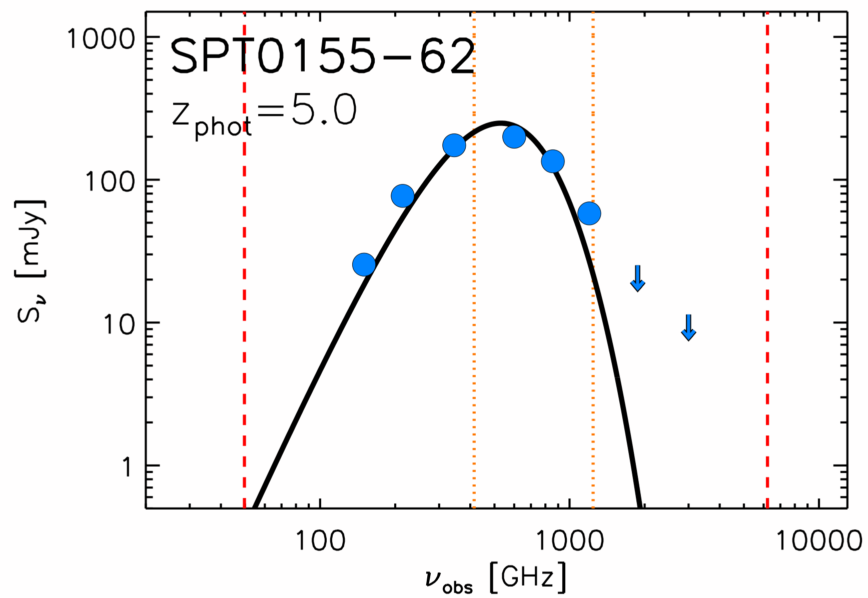


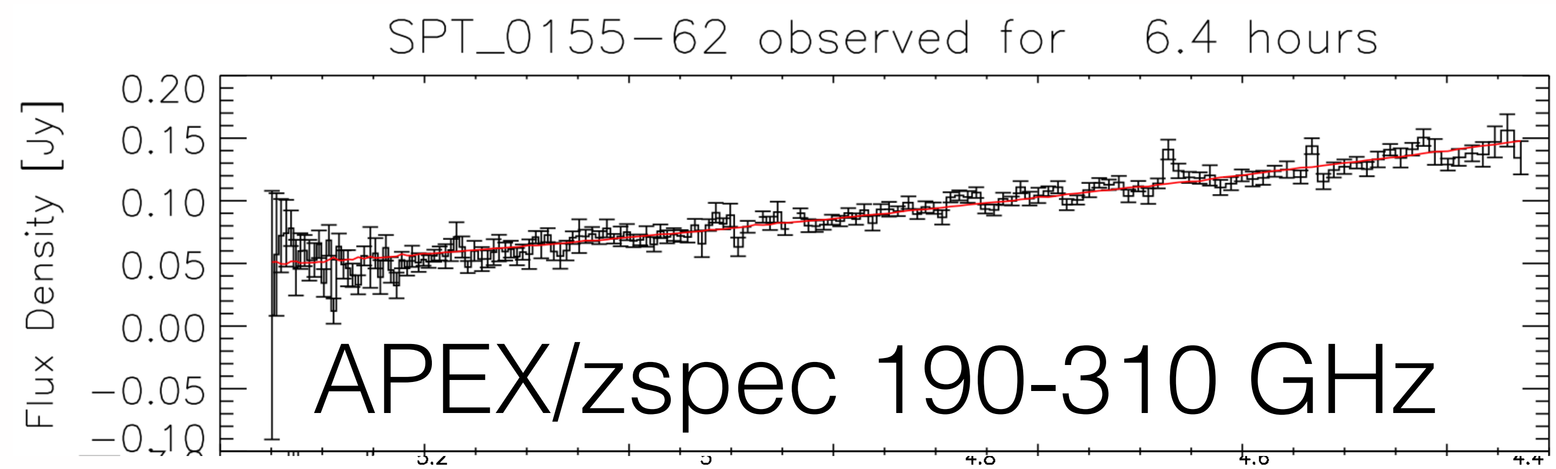


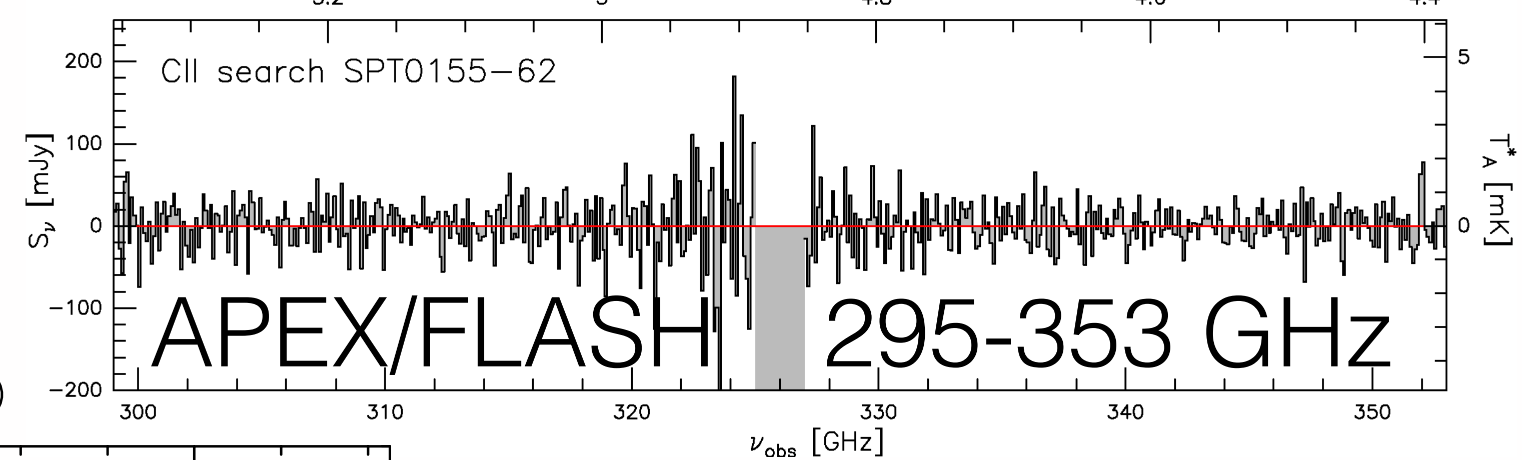
- Brightest DSFG in our SPT sample.
- Scans with APEX covering 190 to 353 GHz showed no lines.

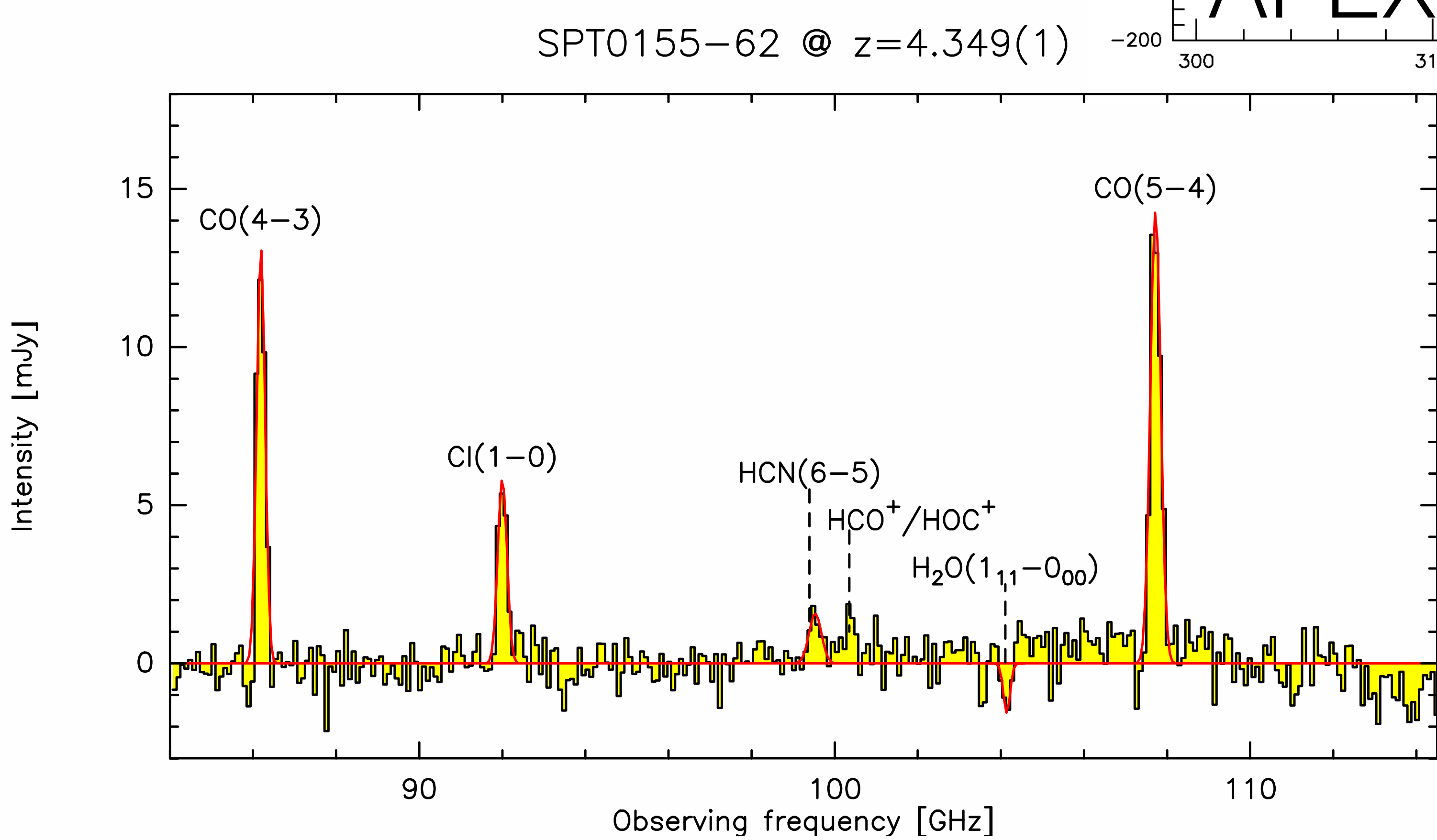
Strandet et al. in prep.

Especially exciting sources





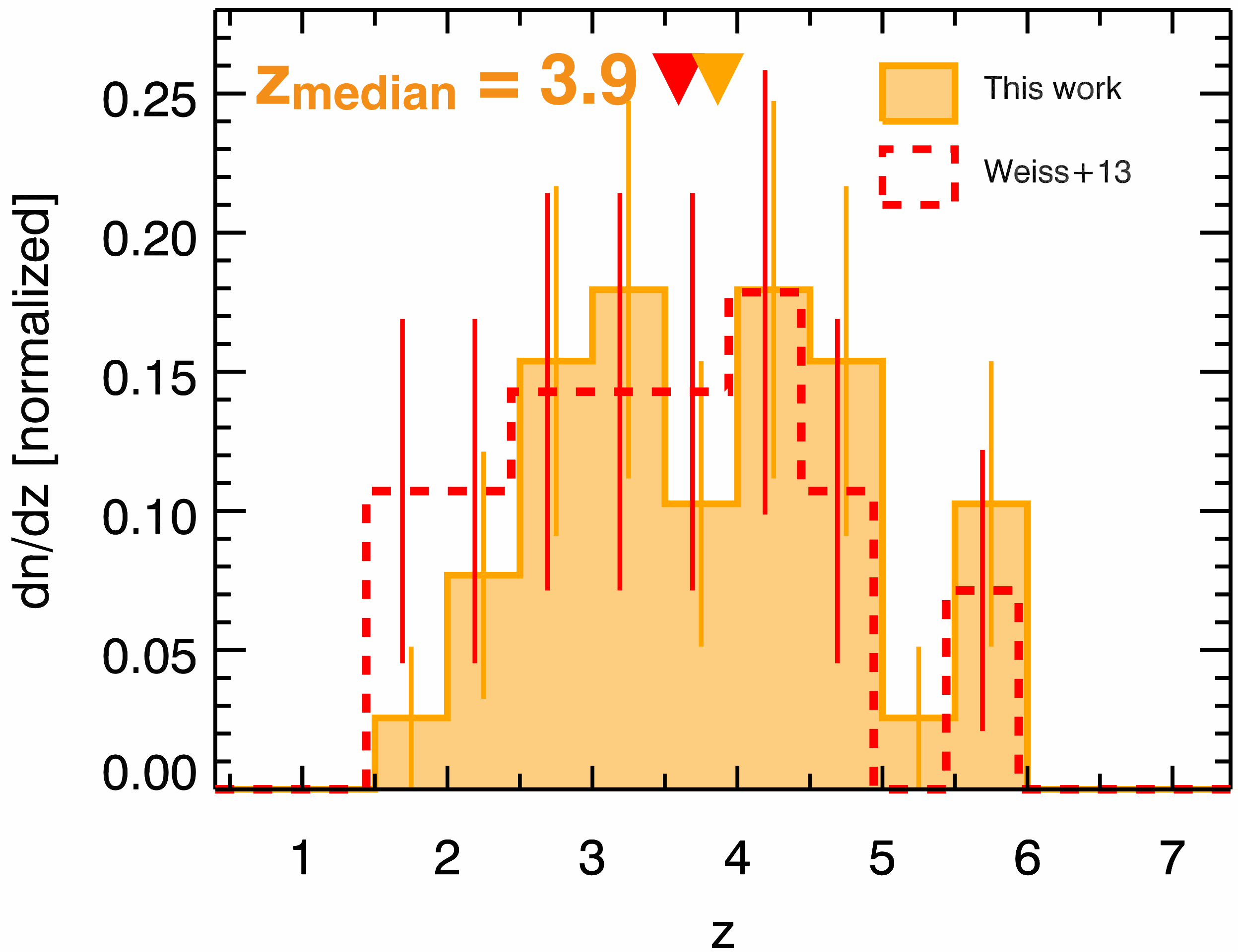


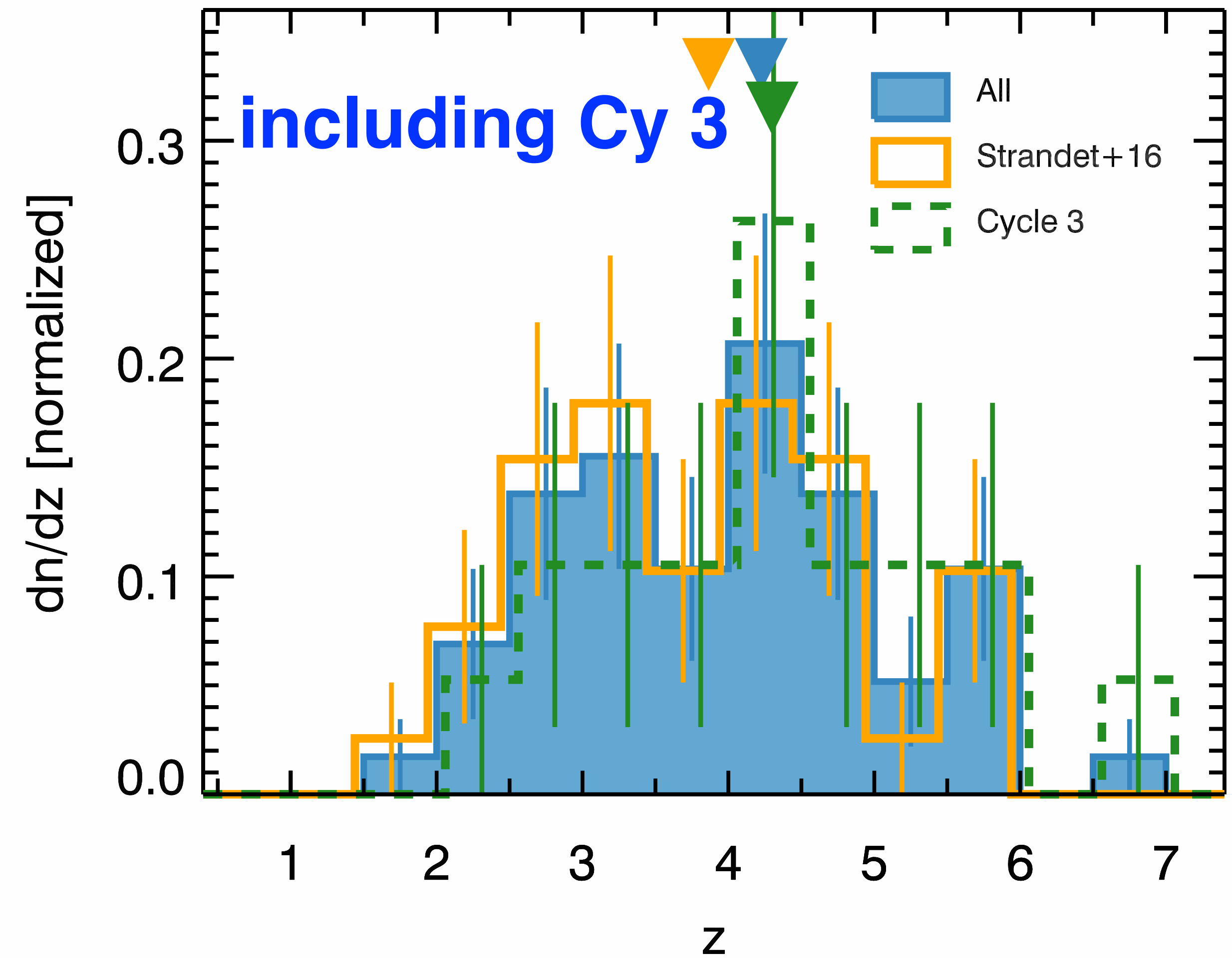


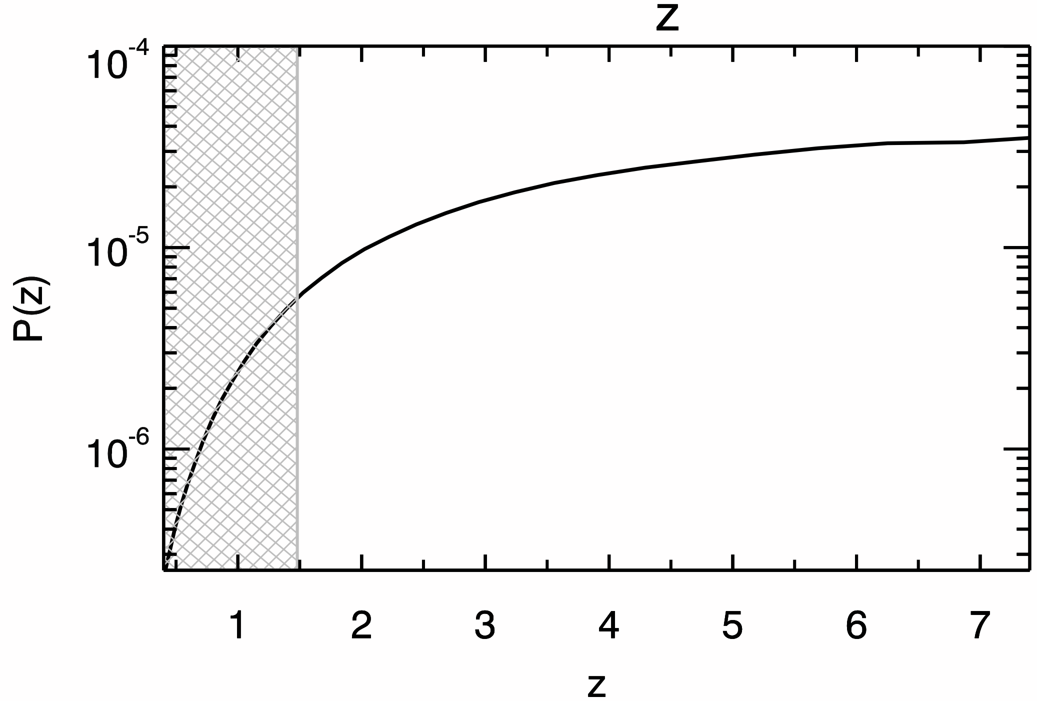
- Brightest DSFG in our SPT sample.
- Scans with APEX covering 190 to 353 GHz showed no lines.
- ALMA band 3 shows many bright lines at z=4.349.
- We just missed [CII] at 355.3 GHz.

Strandet et al. in prep.

Redshift distribution (59 sources)



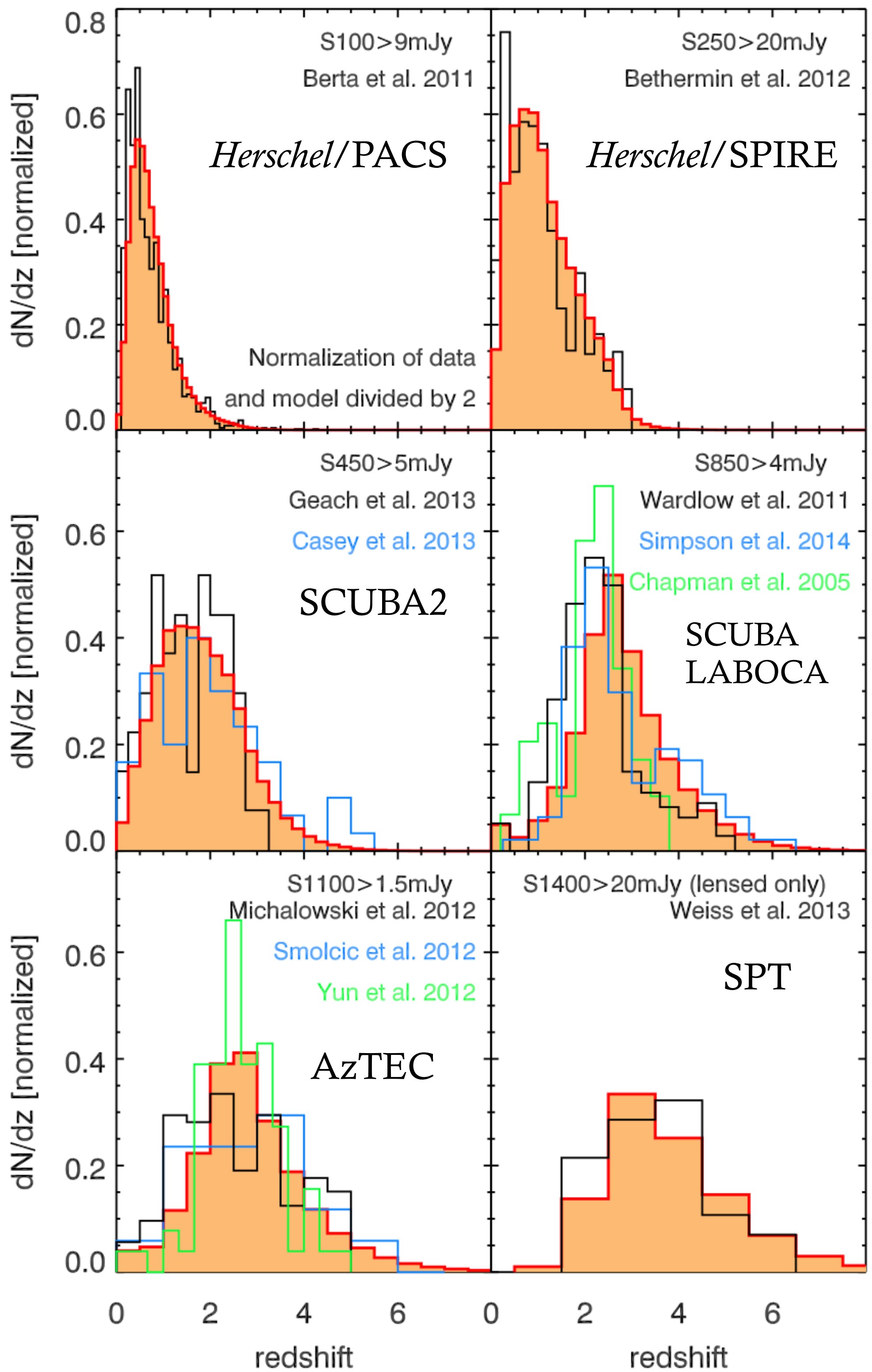


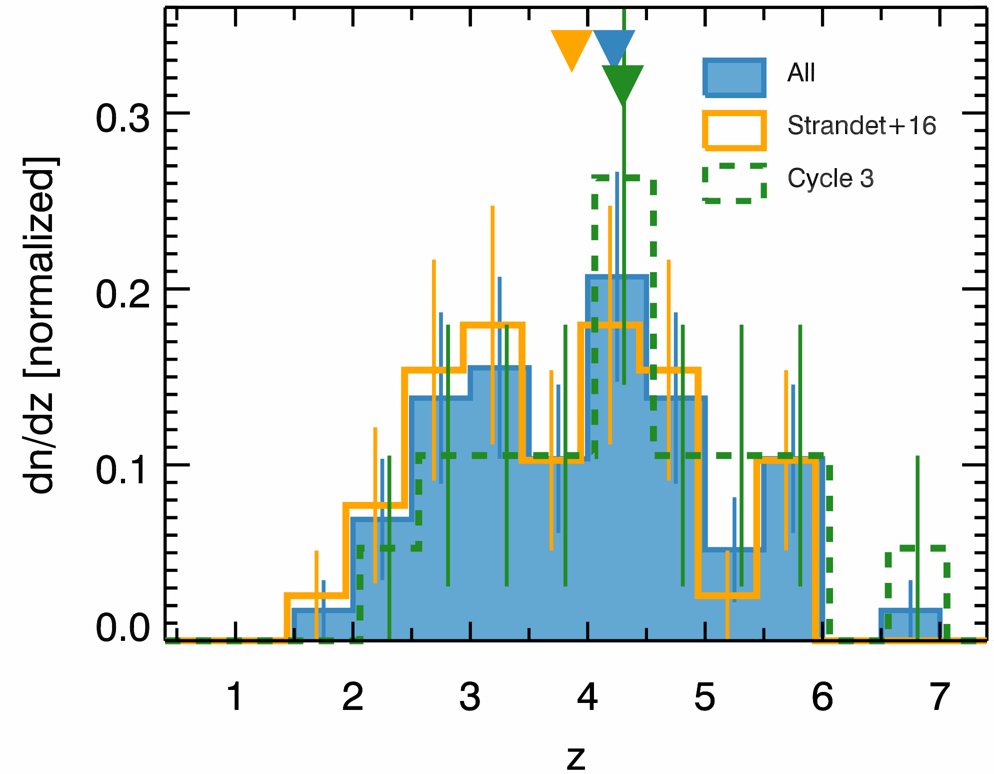


- All redshifts based on ≥2 molecular lines.
- Median redshift 3.9.
- Lensing probability can shift median up by 0.8, but depends on source size evolution with z.

Strandet et al. 2016

Why are the SPT DSFGs at higher redshift?





Matthieu Béthermin

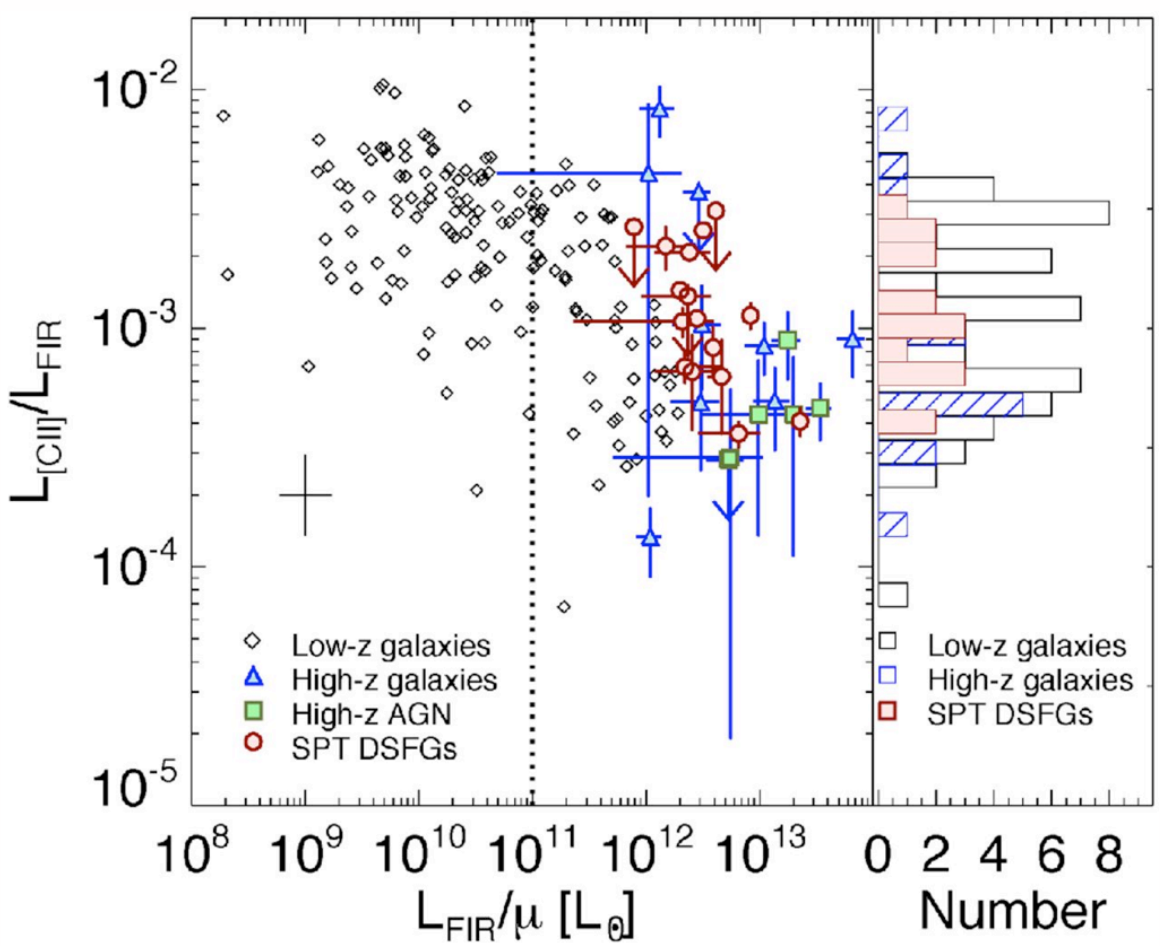
- Galaxies selected at longer wavelength are at higher z.
- Trend well reproduced by the Béthermin+ 2012 model.
- Empirical model with two populations of galaxies: main sequence + starbursts.
- SPT sample contains:
  - ➡lensed main sequence galaxies
  - ➡lensed starbursts
  - ➡extreme unlensed starbursts

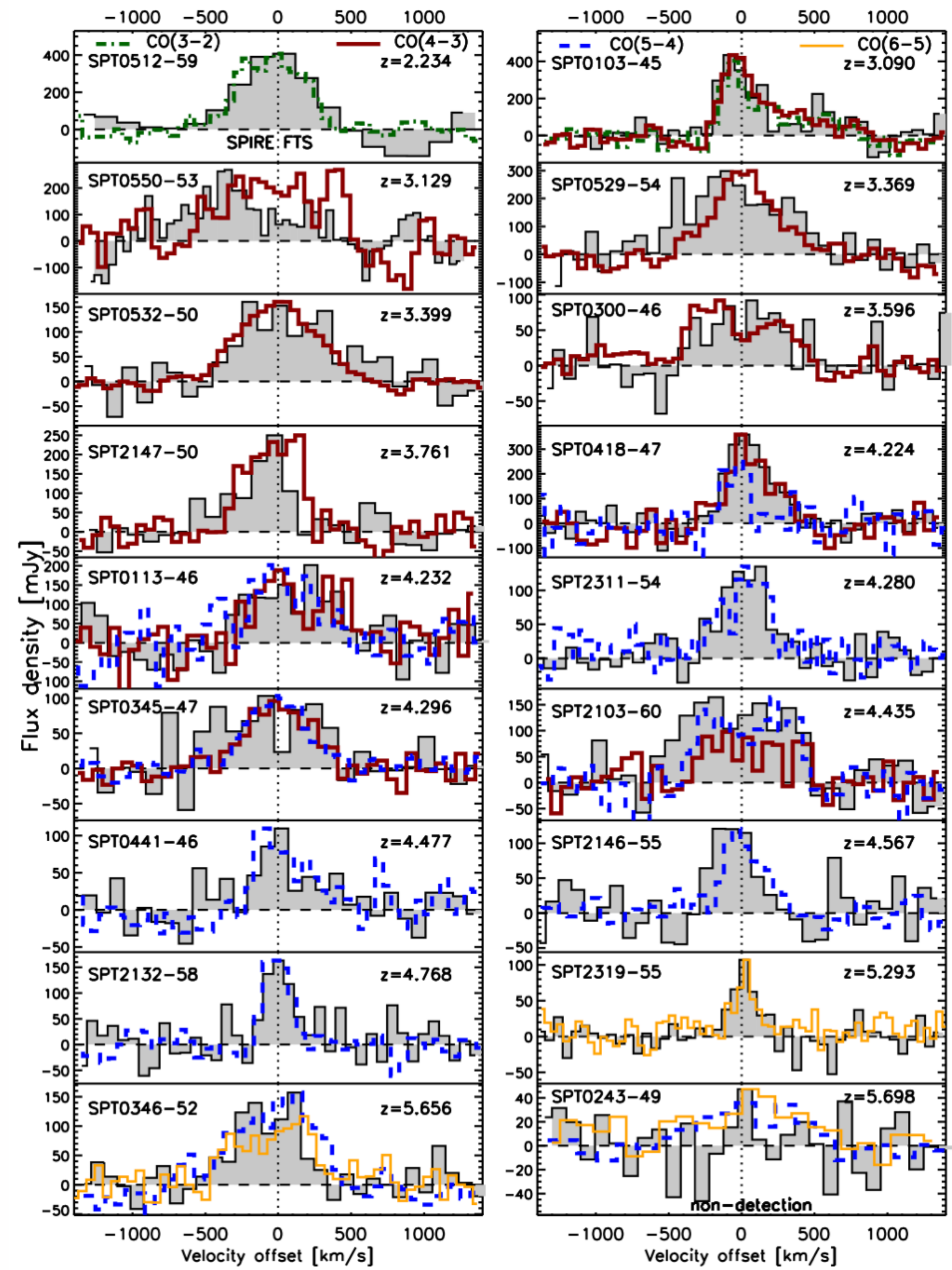
Strandet et al. 2016, Béthermin et al. 2016

APEX SPT [CII] survey

Bitten Gullberg

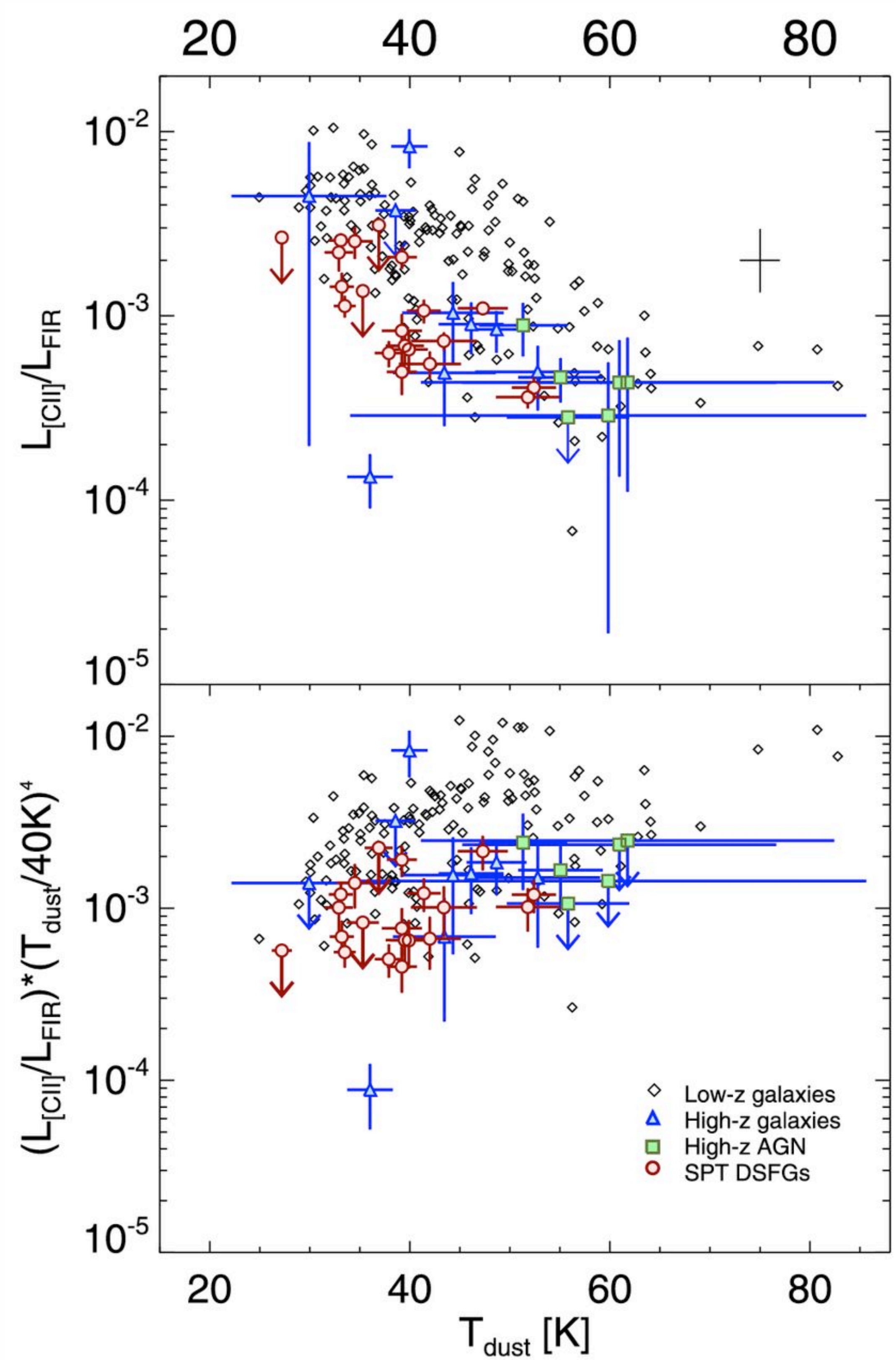
- Clear detections in few hours with FLASH.
- Most systematic high-z [CII] survey to date.
- [CII]/FIR decrement at high L_{FIR} consistent with other samples, but better S/N.



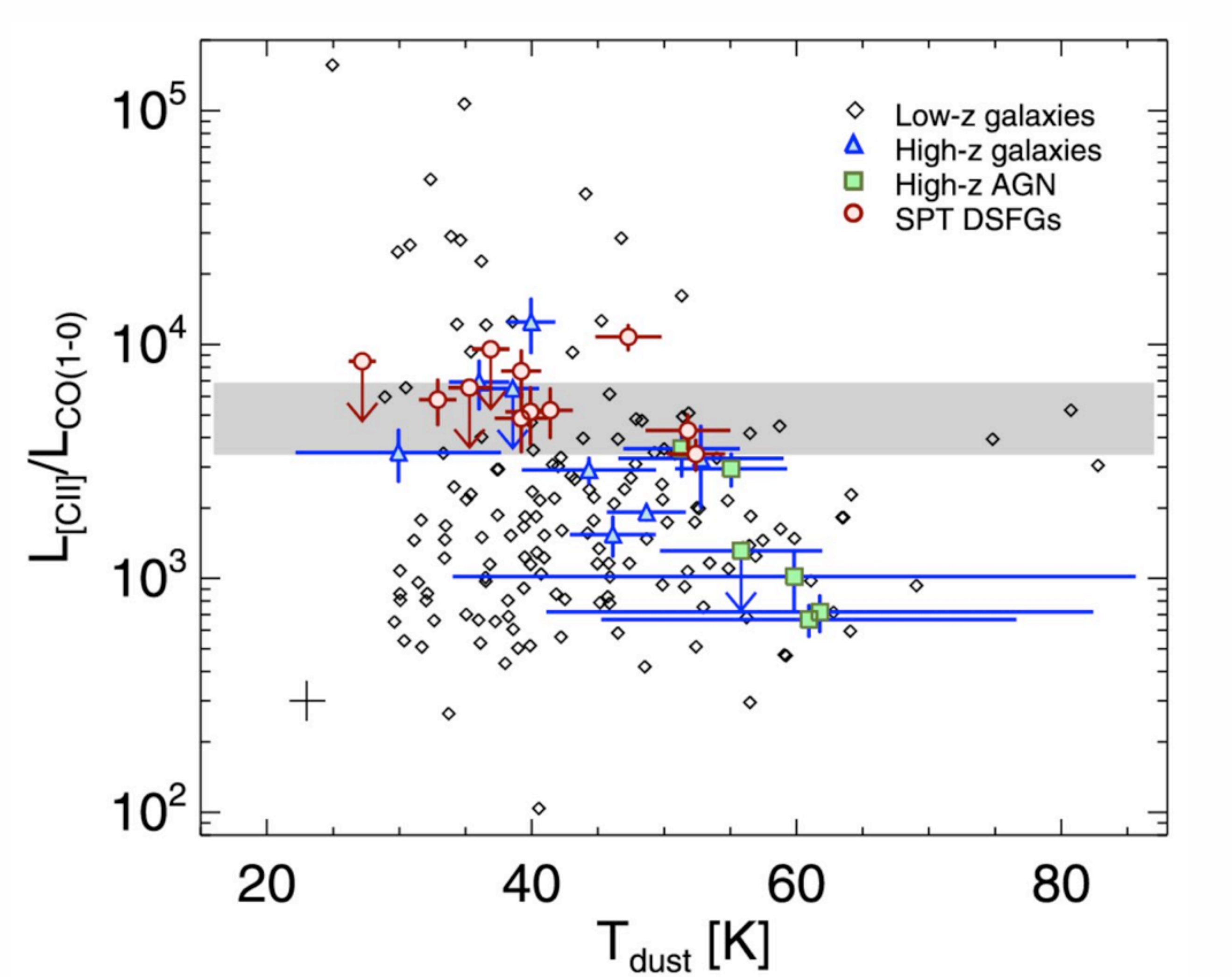


Gullberg et al. 2015

Comparing [CII] with LFIR and CO



- [CII]/L_{FIR} ratio is dominated by Stefan-Boltzmann law $L_{FIR} \propto T^4$.
- [CII] and CO(1-0) luminosities are remarkably closely related.

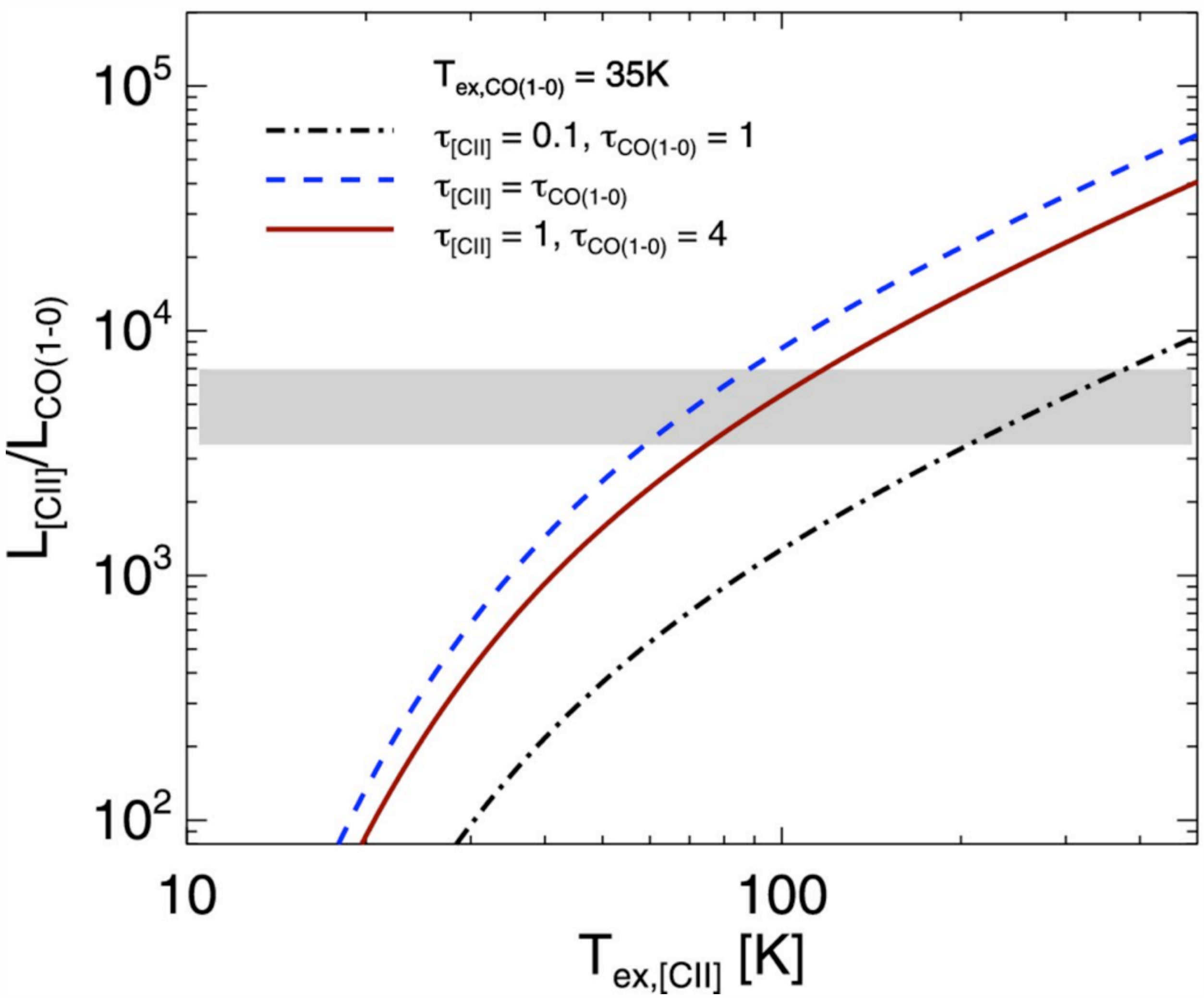


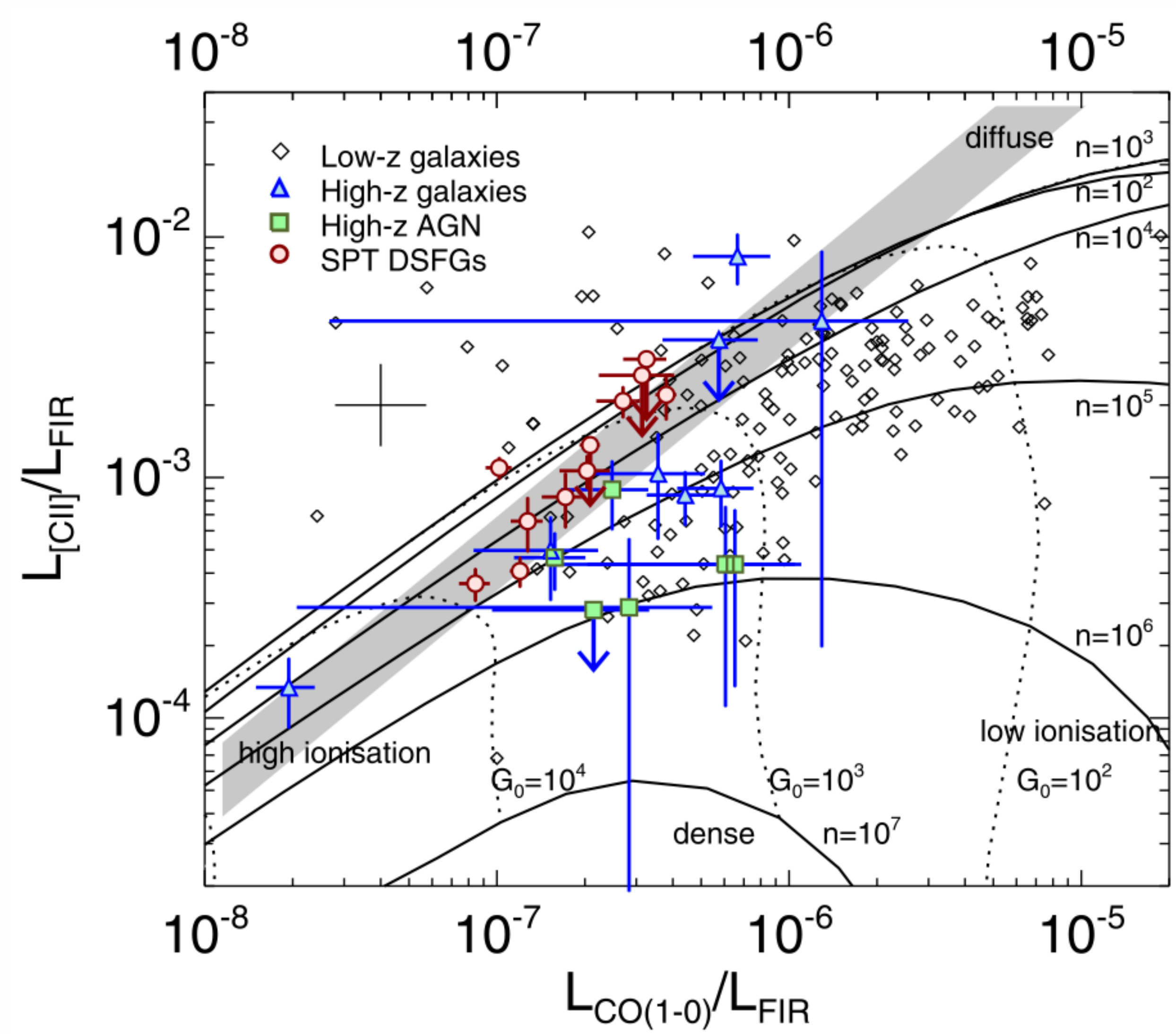
Gullberg et al. 2015

Implications of the constant [CII]/CO ratio

- Comparison of source functions shows that observed [CII]/CO ratio implies moderate optical depth up to 1 and T_{ex}([CII]) > T_{ex}(CO).
- Implies medium of separated CO and [CII] emitting gas like in PDR models.

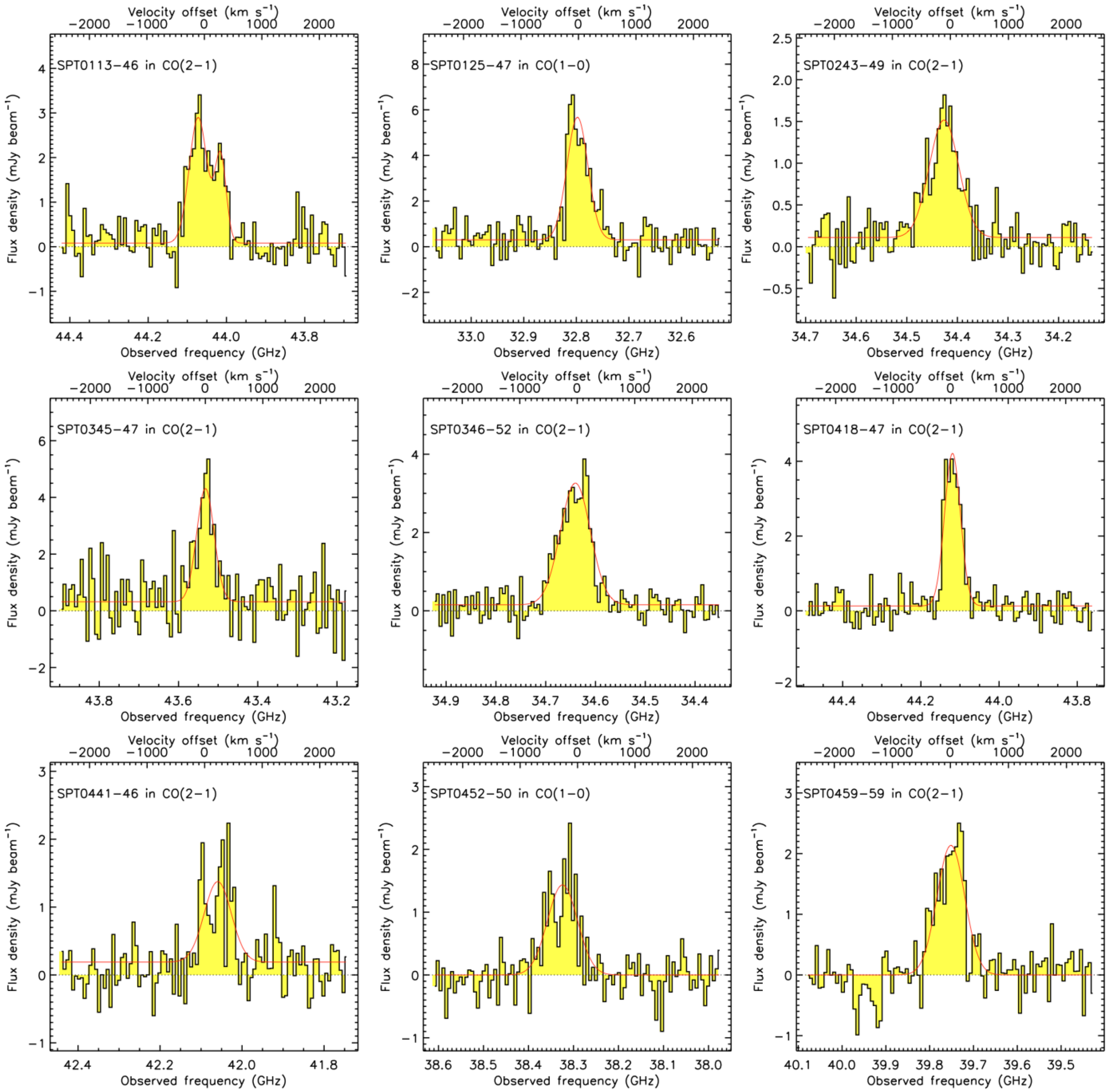
$$\frac{L_{[CII]}}{L_{CO(1\text{-}0)}} = \left(\frac{\nu_{[CII]}}{\nu_{CO(1\text{-}0)}}\right)^4 \times \frac{e^{h\nu_{CO(1\text{-}0)}/hT_{ex,CO(1\text{-}0)}} - 1}{e^{h\nu_{[CII]}/hT_{ex,[CII]}} - 1} \cdot \frac{1 - e^{-\tau_{[CII]}}}{1 - e^{-\tau_{CO(1\text{-}0)}}}$$



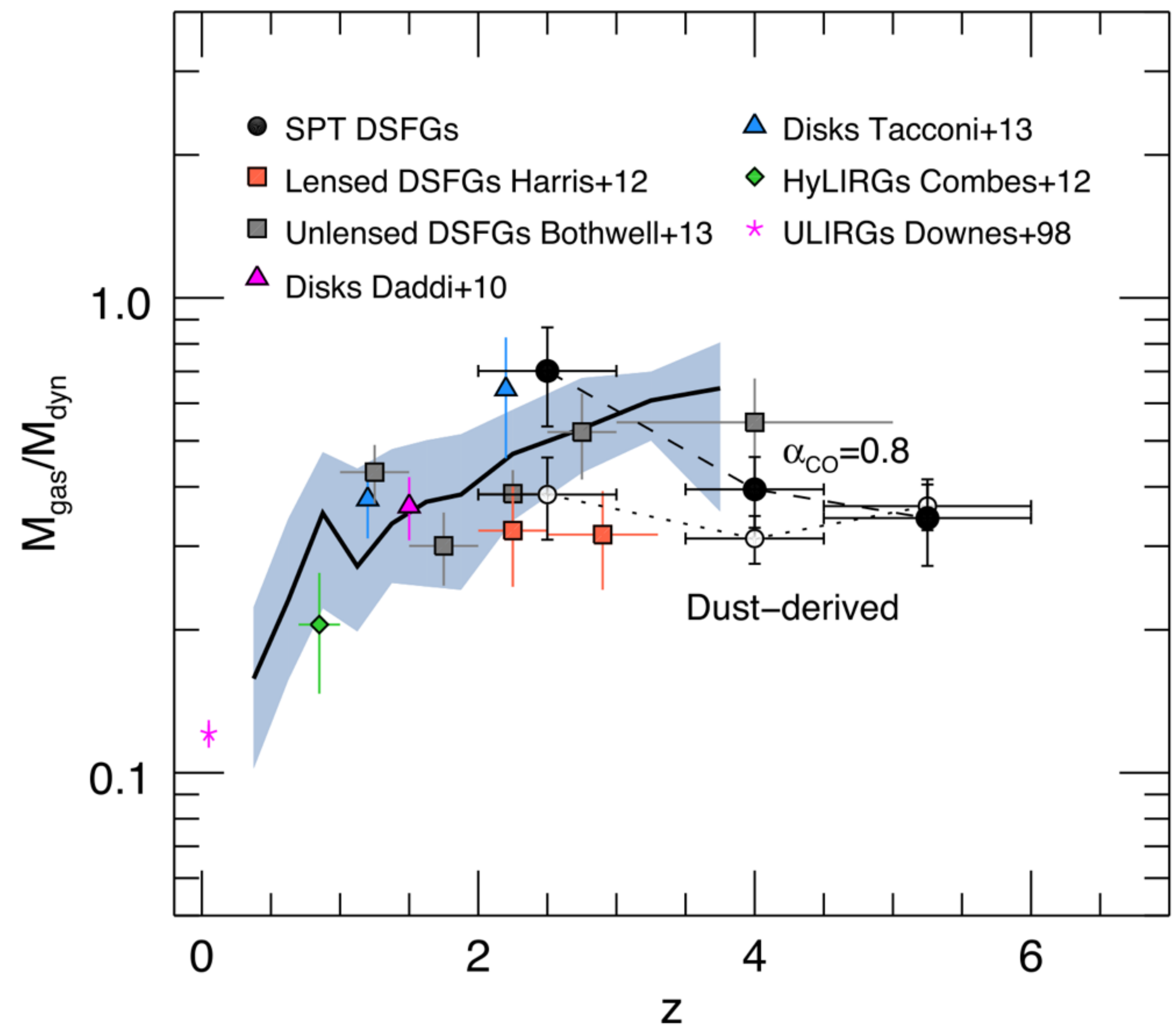


Gullberg et al. 2015

ATCA low-J CO survey



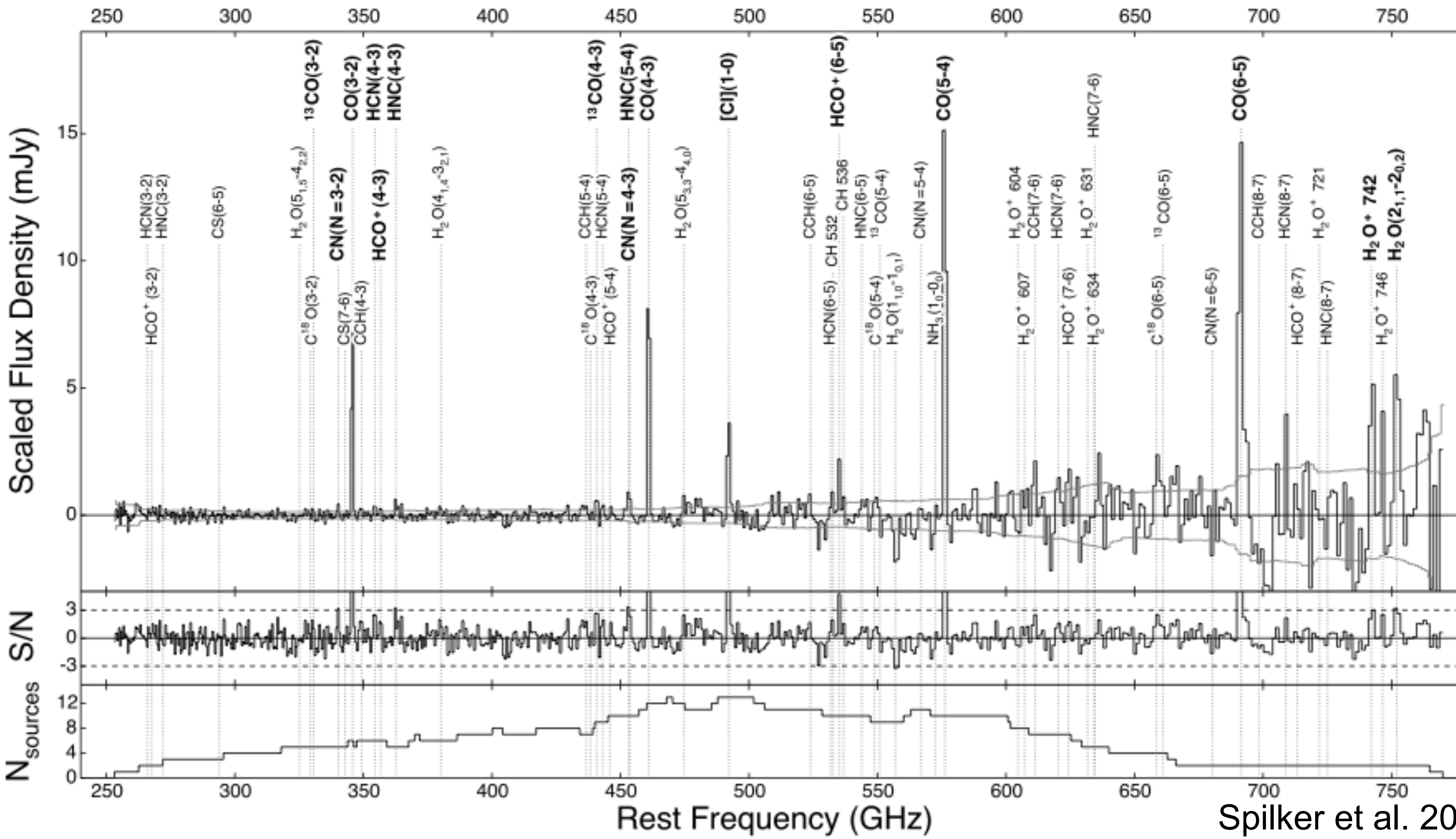
Manuel Aravena



- High S/N detections in <10h in 17 sources.
- Combined with source sizes from lens models → M_{dyn} → gas fraction.
- Gas fraction appears to be constant or slowly decreasing at z>2.

Aravena et al. 2015

Stacked ALMA spectra

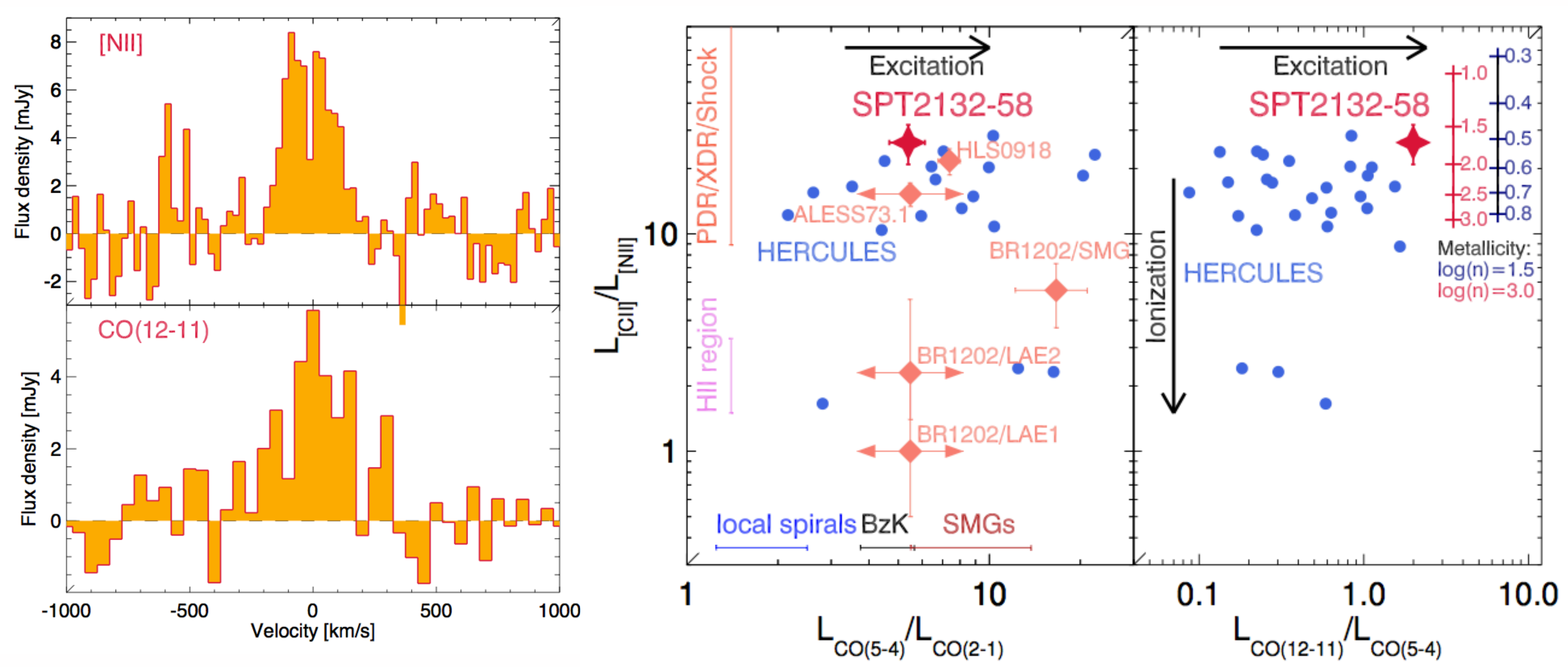


Spilker et al. 2014

^{12}CO, ^{13}CO, [CI], H_2O, HCN, HNC, HCO^{+} and CN
indications of CH and CCH

Spilker et al. 2014

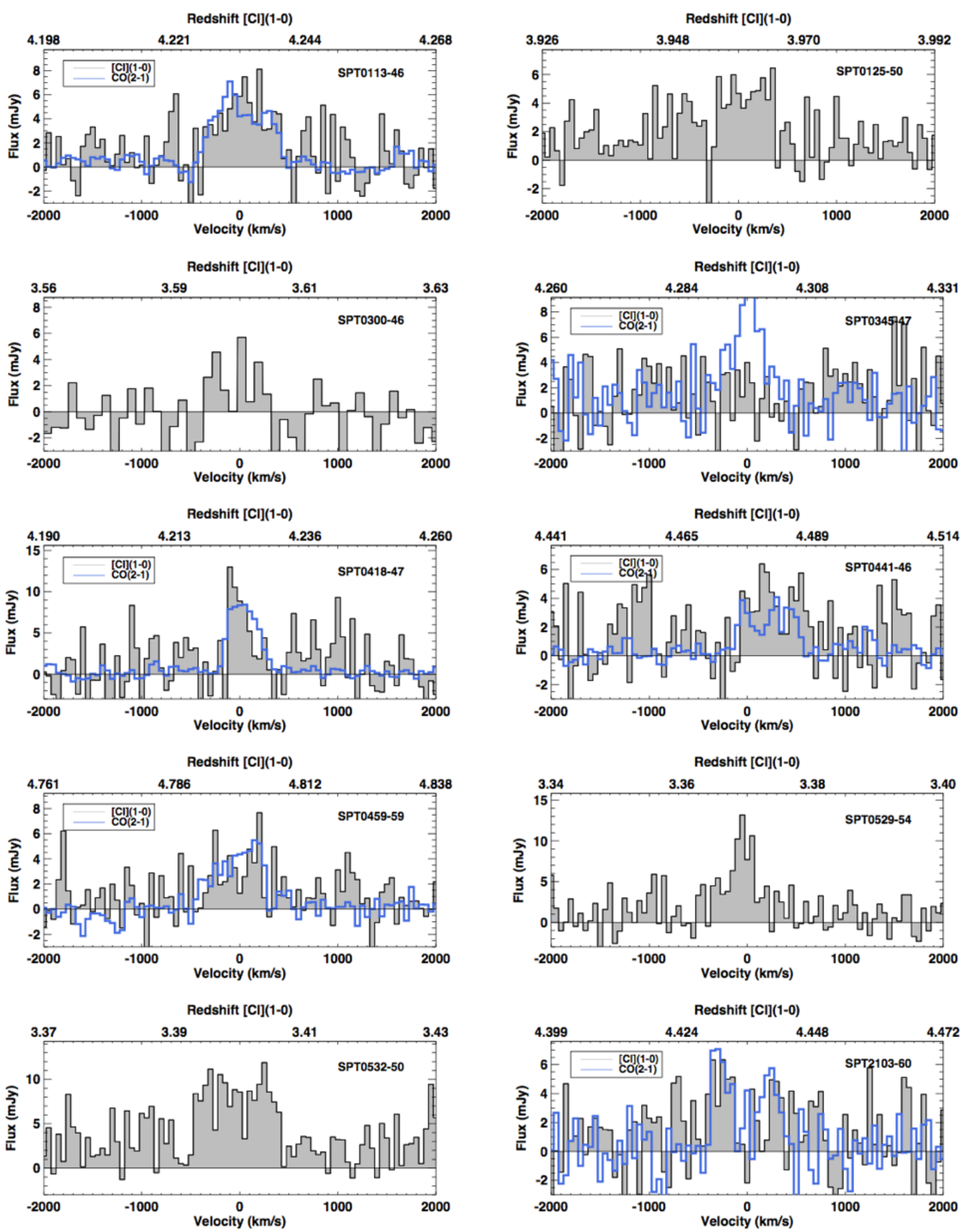
[NII] and high-J CO

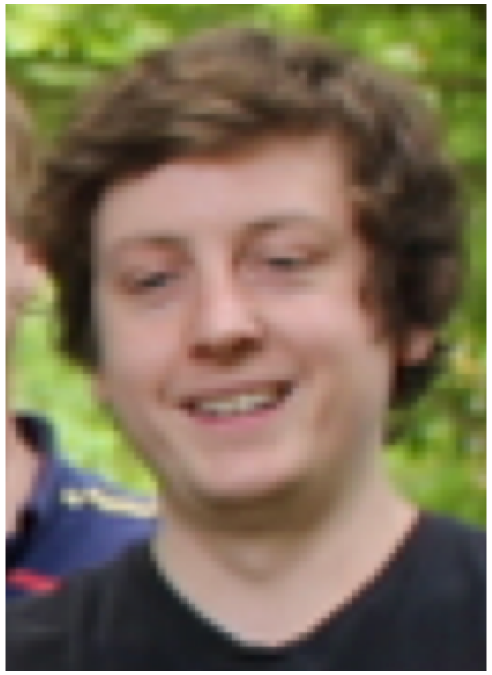


- High [CII]/[NII] ratio PDR dominates over HII regions.
- Indication of lower metallicity?

Béthermin et al. 2016

ALMA + APEX [CI] survey



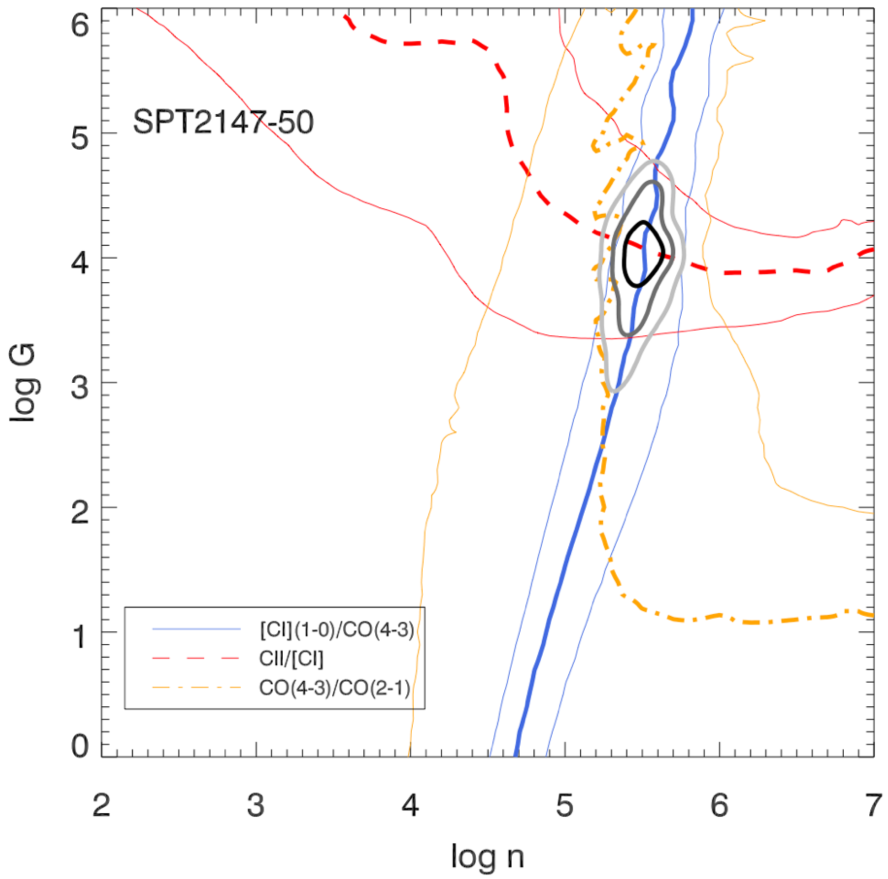


Matt Bothwell

- [CI]609μm line often within ALMA band 3 spectra.
- Most uniformly selected [CI] sample to date.

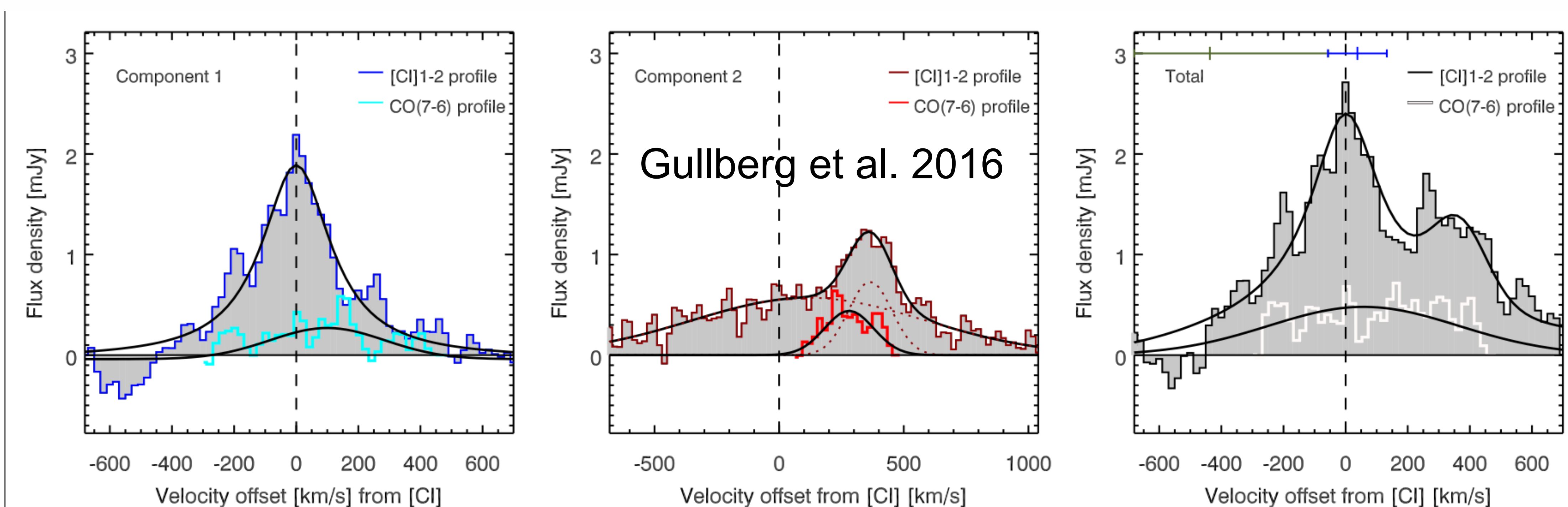
Bothwell et al. in prep.

Advantages and uncertainties of [CI]



Bothwell et al. in prep.

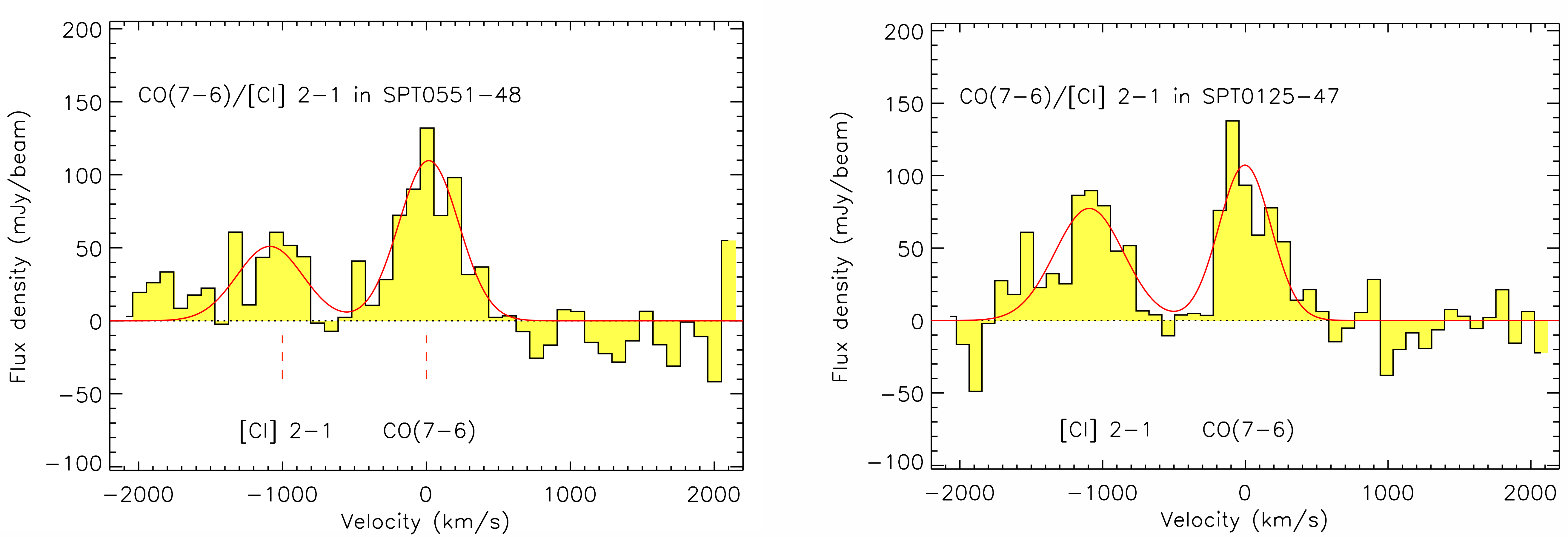
- Combine [CI] with [CII] and CO(1-0) to constrain PDR models.
- 3D-PDR models suggest denser ISM than previous models.
- [CI] provides alternative M(H_2) tracer:
  - ➡independent α_{CO} determination
  - ➡needs assumption on $X_{[CI]}$
  - ➡distribution of flux between both [CI] lines may vary substantially with excitation e.g in AGN.
  - ➡informal discussion on Friday



Gullberg et al. 2016

[CI] 370μm survey with APEX/SEPIA

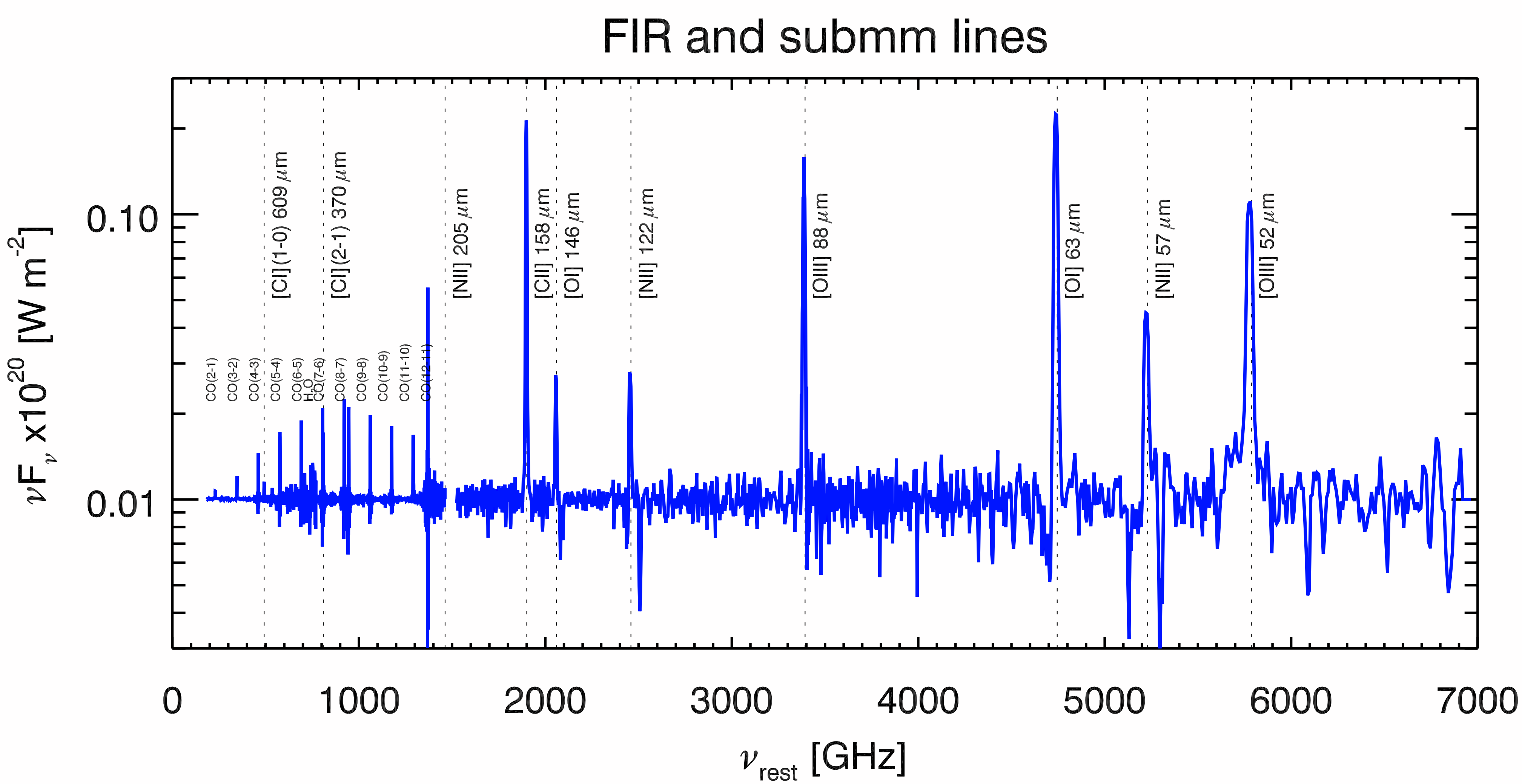
- First [CI] 2-1 370μm detections with APEX/SHFI.
- New band 5 receiver in SEPIA covers [CI]370μm at 2.8<z<4.1, large overlap with [CI] 1-0 690μm in ALMA band 9.
- Observations just started, showing variations in CO(7-6)/[CI]690μm ratio.



Béthermin, Gullberg et al.

Other fine-structure lines

- With 59 bright DSFGs covering 1.9<z<6.9, the SPT sample is ideally suited to start surveys of all bright far-IR FSL:
  - ➡ check if [CII] deficit also holds for other FSL
  - ➡ use line ratios to constrain density, temperature, HII/PDR fraction, ionization parameter, metallicity, ...



Conclusions

The SPT DSFG sources are almost all lensed by foreground galaxies, with a **median magnification μ=6.3**.

We have determined unambiguous redshifts for **59 sources** out to z=6.9, and with **median z=3.9±0.4**.

The **higher redshift** compared to other DSFGs is mostly due to the **longer selection wavelength** and gravitational lensing.

Systematic studies of **low-J CO** and **FSL** like [CII] and [CI] provide **key diagnostics of the ISM**: H_2 mass, line opacities, ...

More FSL surveys ([OI]63μm, [OIII]88μm, ...) are becoming possible **thanks to wide redshift coverage** of SPT sample.