THE NATURE OF THE [CII] EMISSION IN LENSED DUSTY STAR-FORMING GALAXIES FROM THE SPT SURVEY

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In collaboration with Carlos De Breuck and the SPT SMG collaboration

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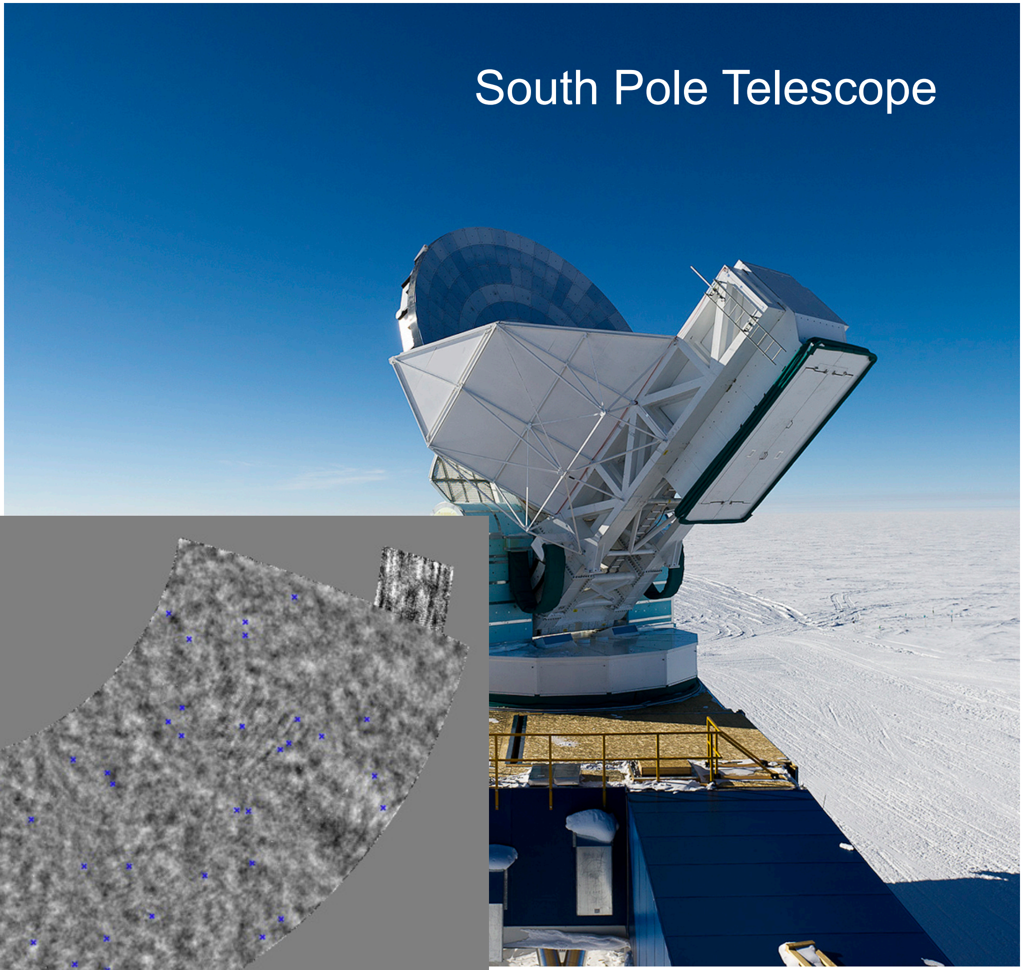
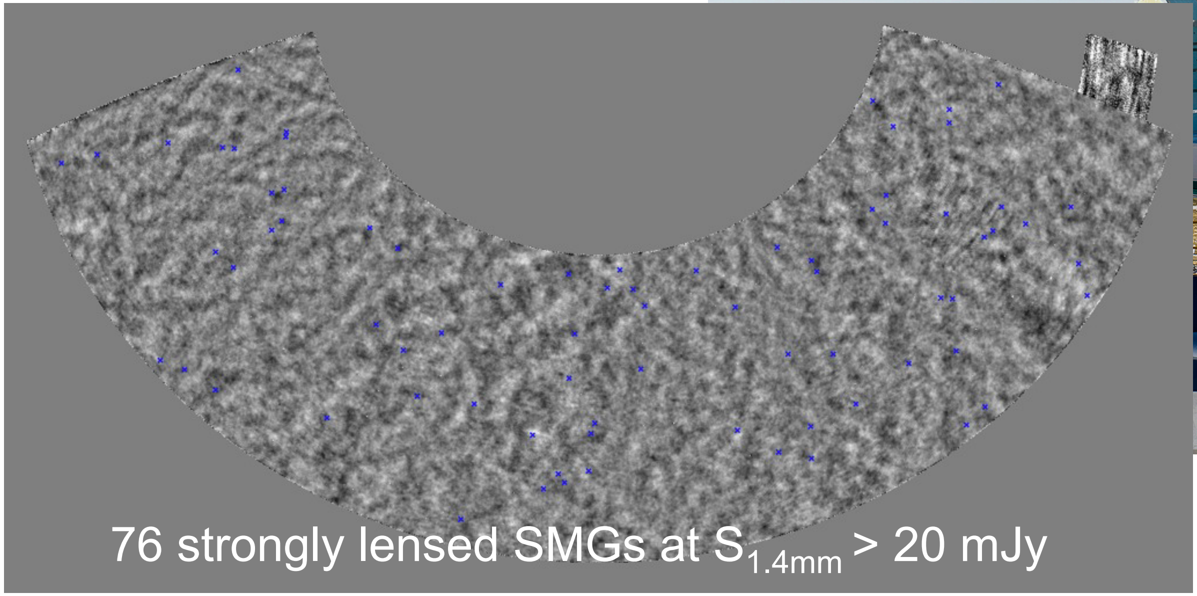
Lensed dusty star-forming galaxies @ high-z

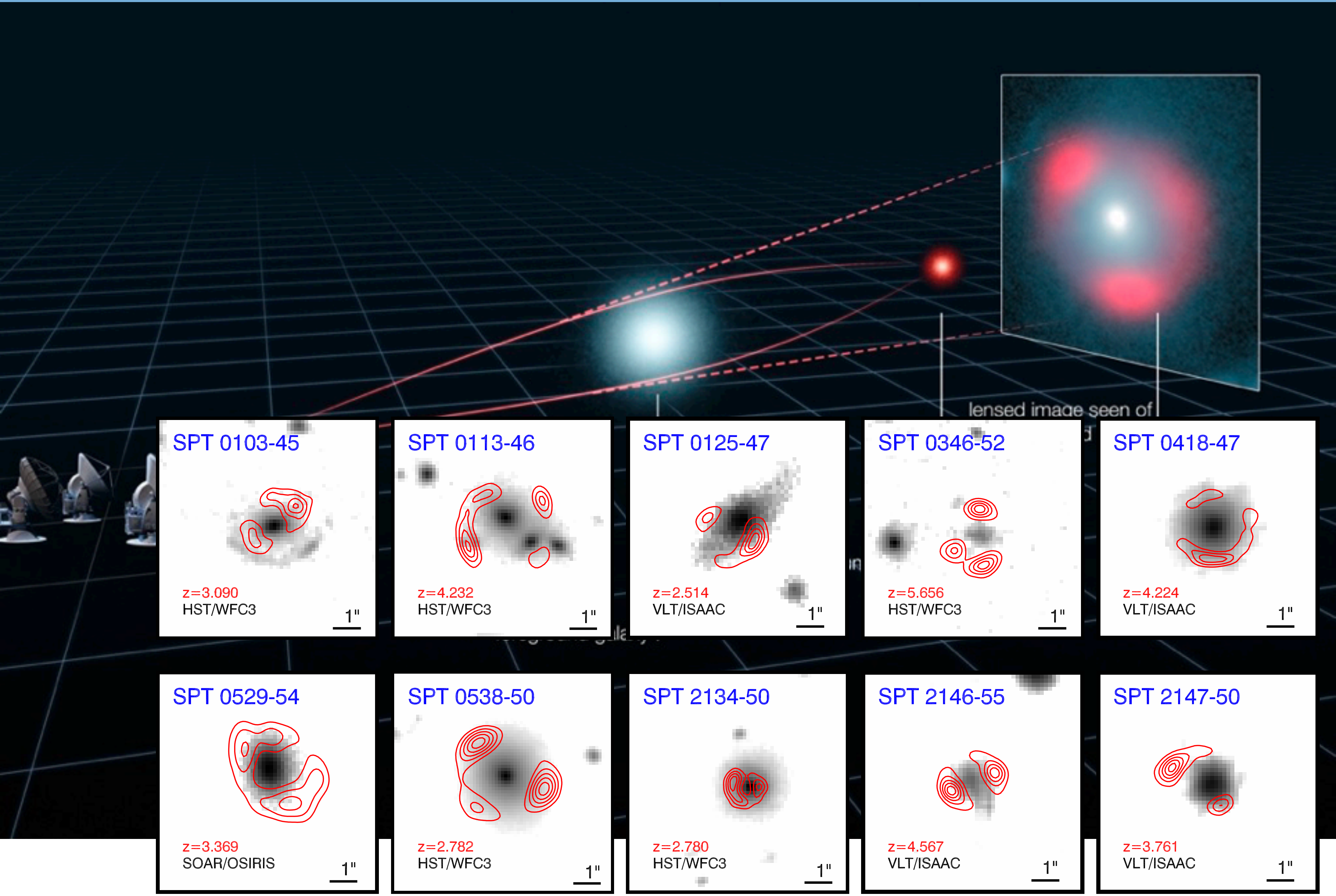
26 SPT sources chosen from the SPT 2500 deg^2 survey observed with ALMA during cycle 0.

CO and/or [CI] lines were observed for 23 sources.

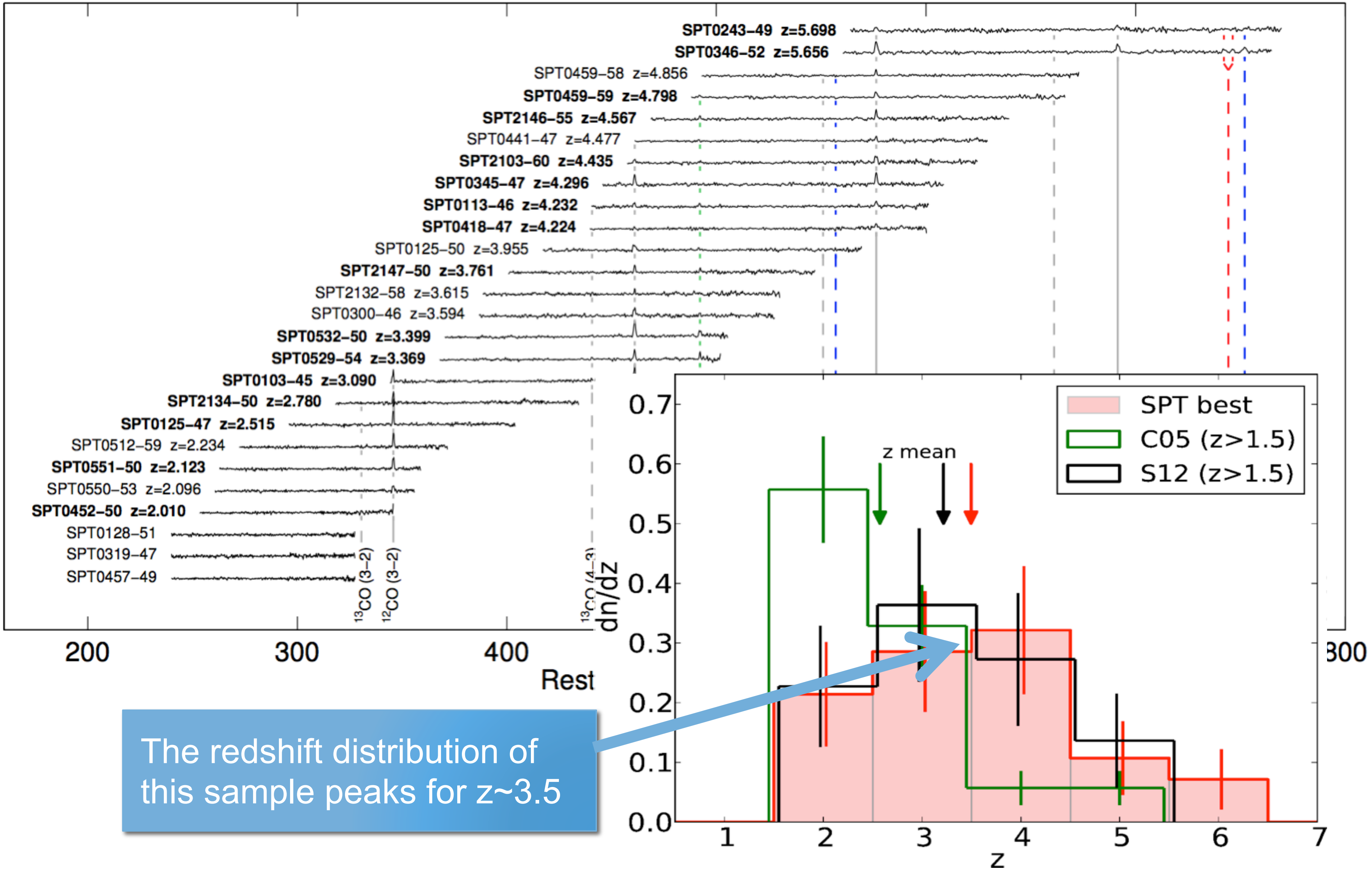
Redshift range: z = 2.010 – 5.678.







NIR (grey) and ALMA 870μm (red) images (J. Vieira et al. Nature 2013)



The redshift distribution of this sample peaks for z~3.5

A. Weiss et al. 2013

Motivation for follow up observations

Low-*J* CO: ATCA → 17/20 detections
[CII]: FLASH/APEX and *Herschel* SPIRE FTS → 17/20 detections

By studying [CII] and CO lines we wish to constrain the physical conditions of the ISM of high-z galaxies.

The lensing amplification of these bright dusty star forming galaxies makes this kind of study possible.

The redshift distribution of this sample covers the peak of the star formation history → good sample for exploring evolutionary effects.

We wish to compare velocity profiles to explore the significance of differential lensing.

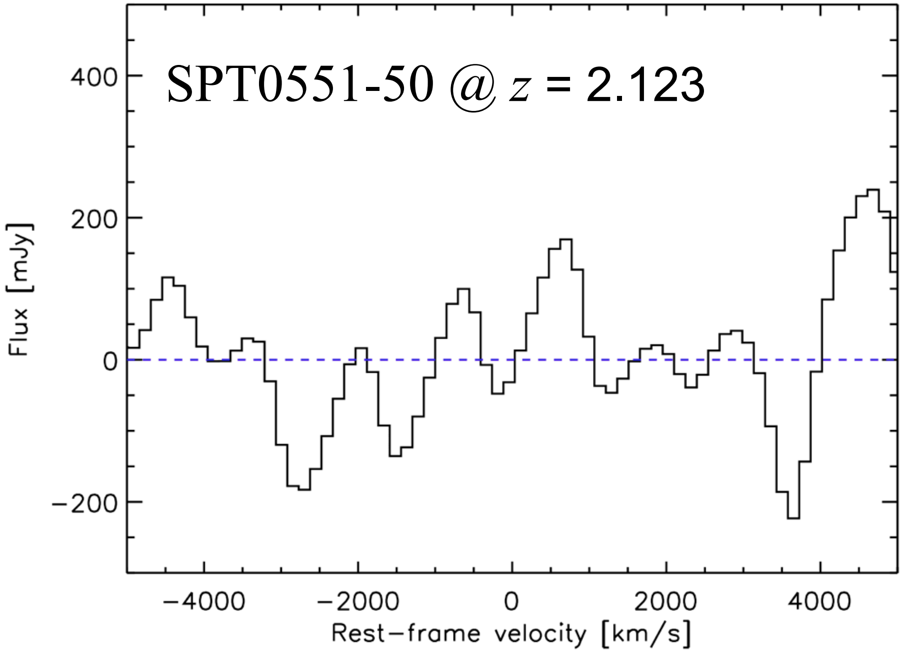
We wish to confirm ambiguous ALMA redshifts (Weiss et al 2013)

Uniform selected sample of lensed dust star-forming galaxies

FLASH @ APEX

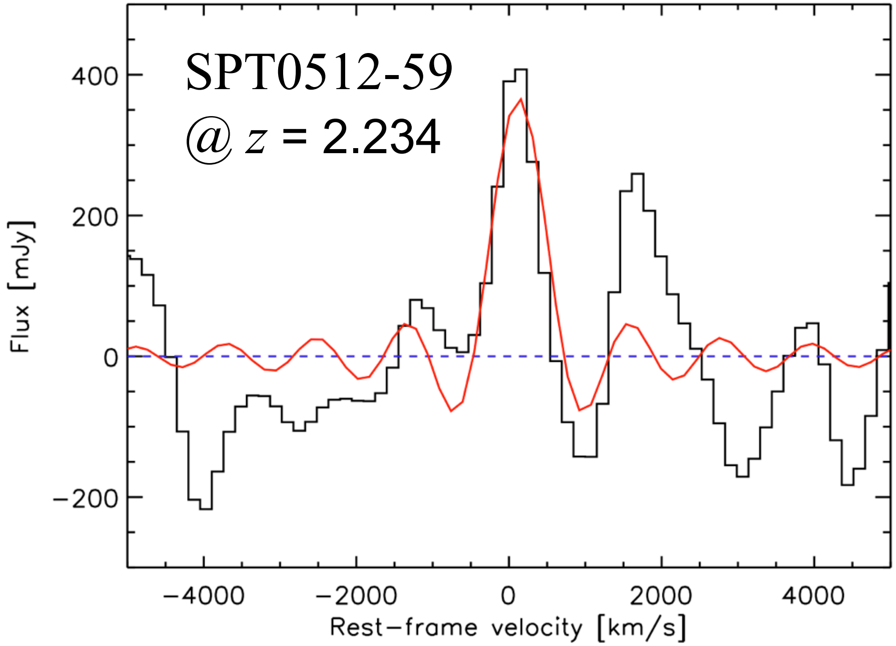
17/20 sources @ z = 3.1 - 5.7 observed with FLASH during Max Planck time
→ 15 detections!

[CII] with *Herschel* SPIRE FTS

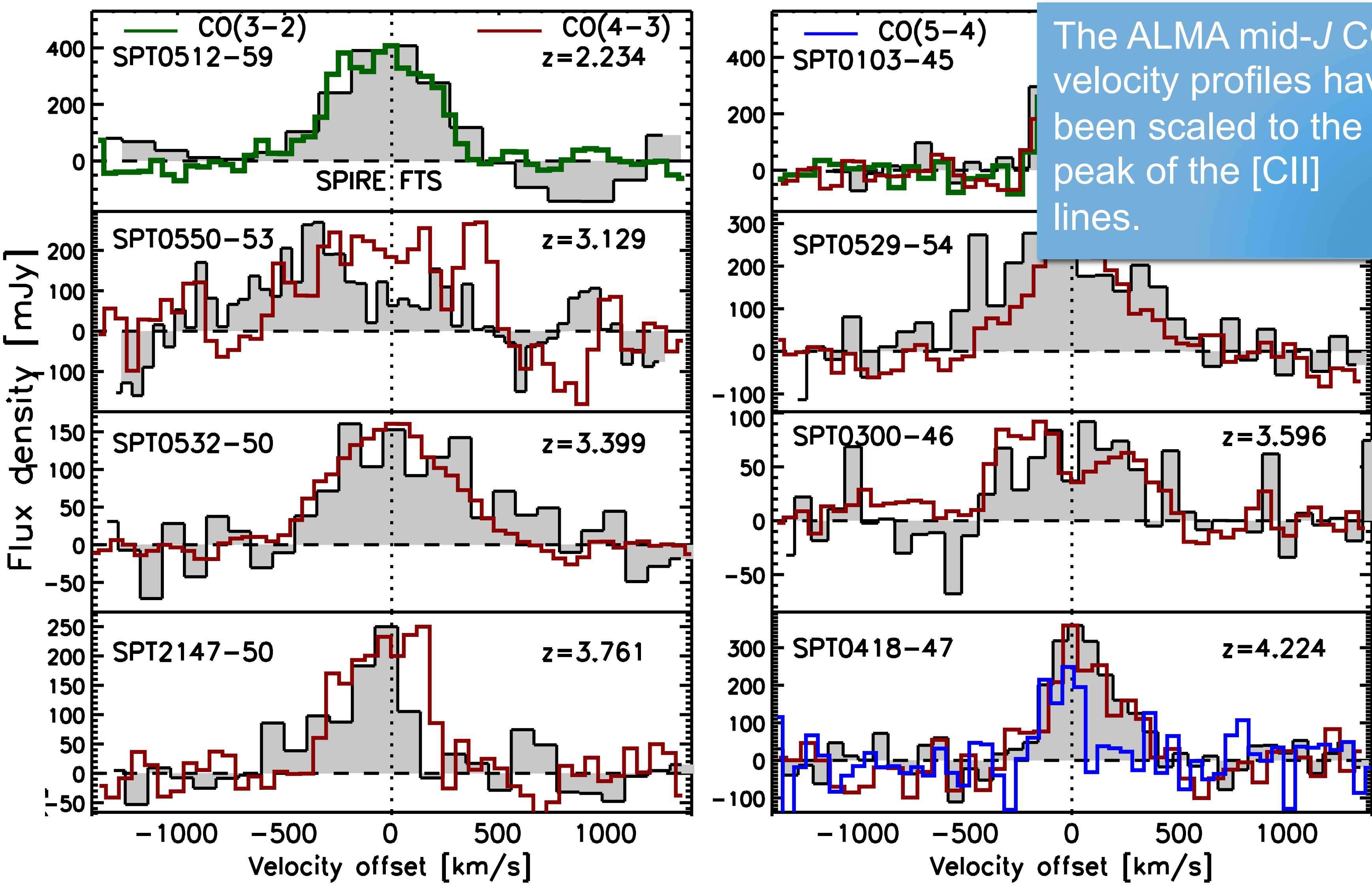


Sources @ z ~ 2 not observable with FLASH.

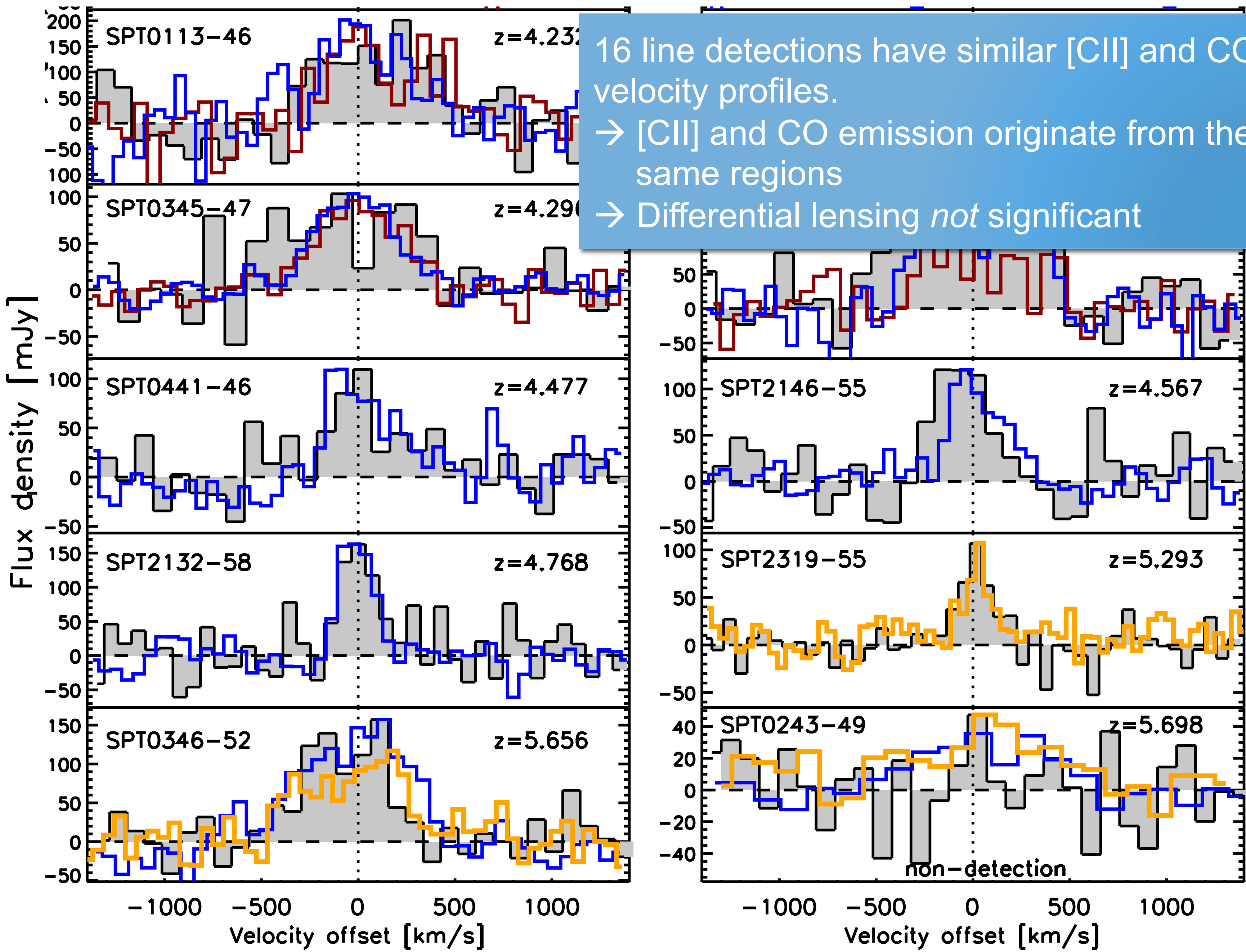
APEX/FLASH can observe weaker lines at higher z



Velocity profiles – Comparing with ALMA



The ALMA mid-*J* CO velocity profiles have been scaled to the peak of the [CII] lines.



16 line detections have similar [CII] and CO velocity profiles.

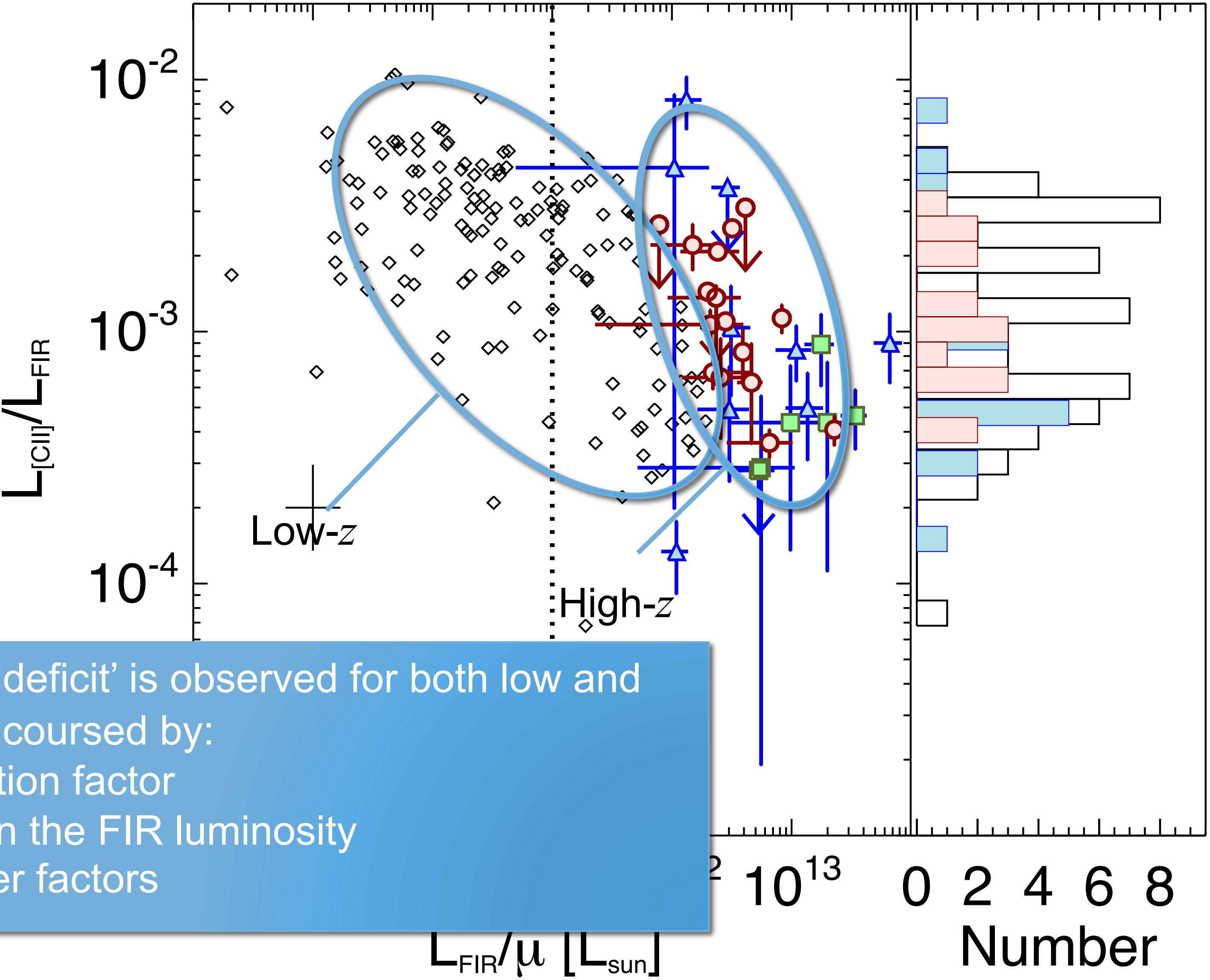
→ [CII] and CO emission originate from the same regions

→ Differential lensing *not* significant

[CII] at high-*z* compared to low-*z*

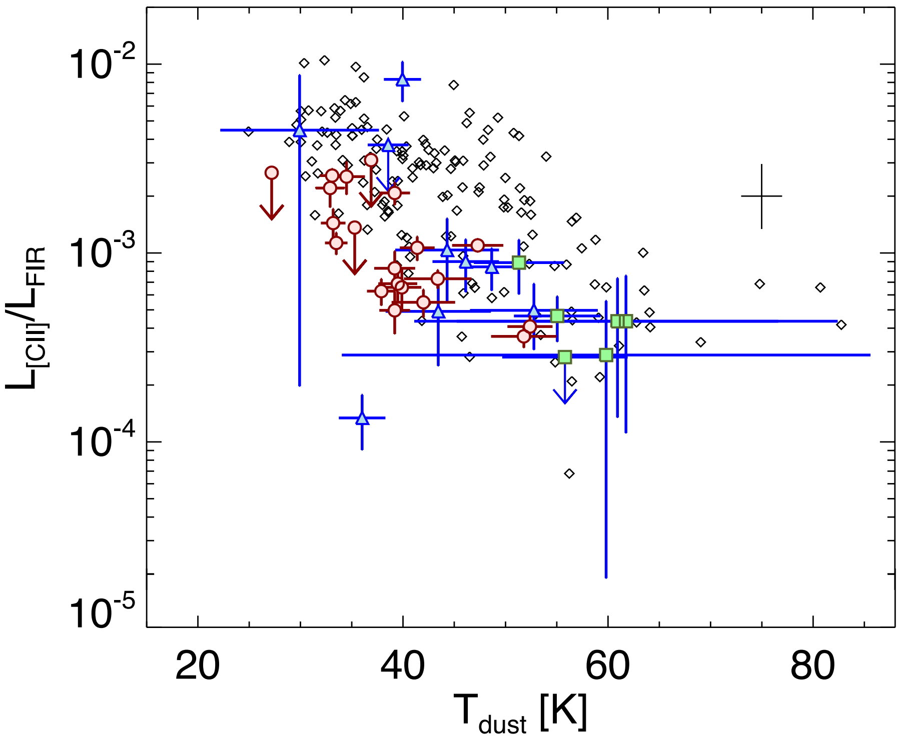
Black dots: compilation of [CII] data for low-*z* sources (Gracia-Carpio in prep). The L_{FIR} is determined in the a consistent way by SED fitting.

Red dots:

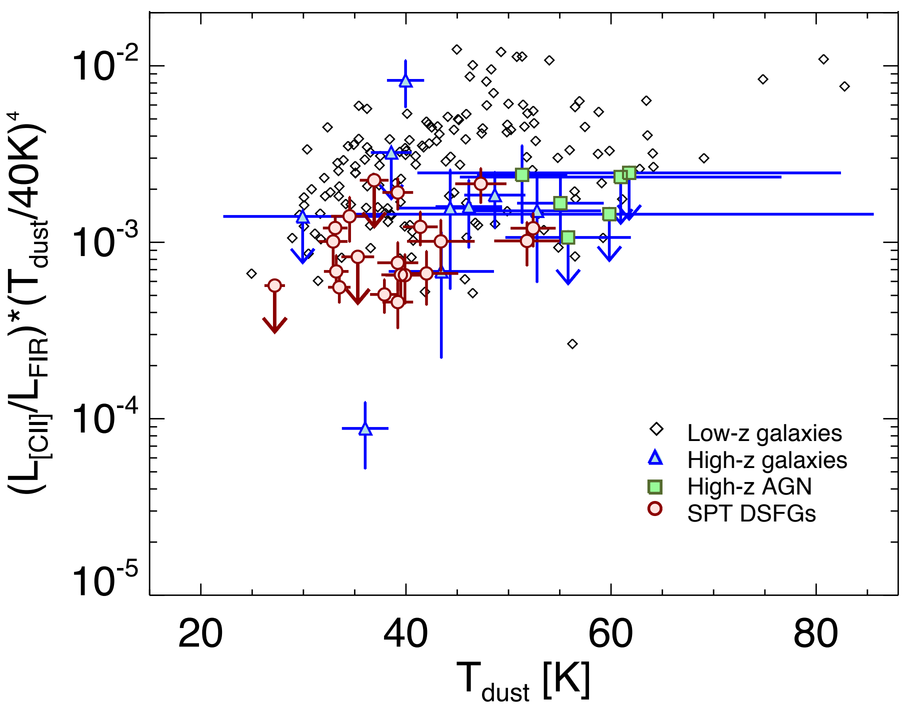


The [CII]/FIR 'deficit' is observed for both low and high-*z* can be coursed by:
→ high ionisation factor
→ variations in the FIR luminosity
→ And/or other factors

[CII] and the dust temperature



$L_{[CII]}/L_{FIR} \rightarrow L_{[CII]}/L_{FIR}/T^4$



Low-J CO with ATCA

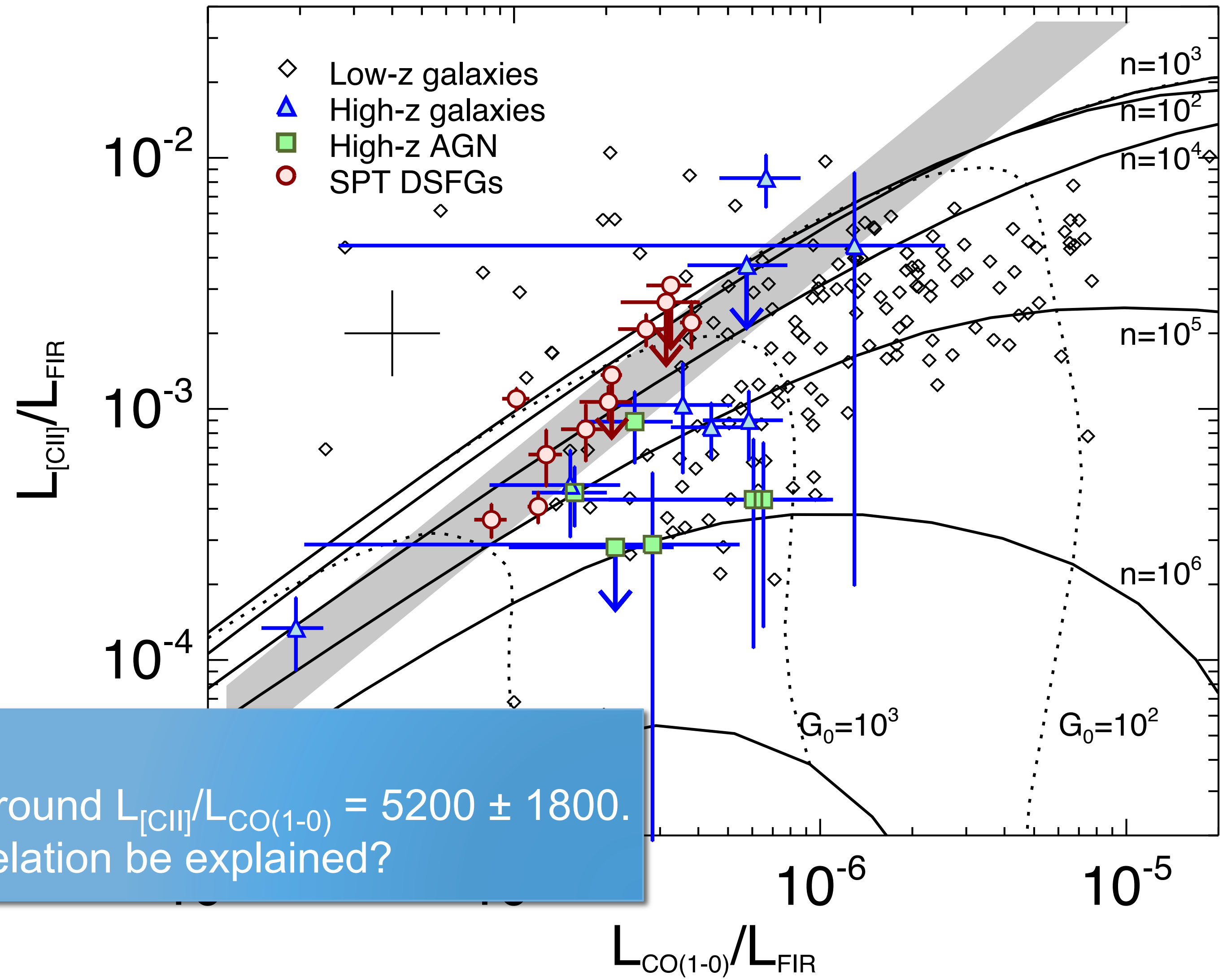
Low-J CO lines for 20 sources observed @ z = 2.0 - 5.7 observed with ATCA
→ 17 detections!

‘Diagnostic’ plot

Photon dominated region (PDR) model

L_{FIR} determined in uniform manner for all

[CII] and CO luminosities integrated over the full galaxies

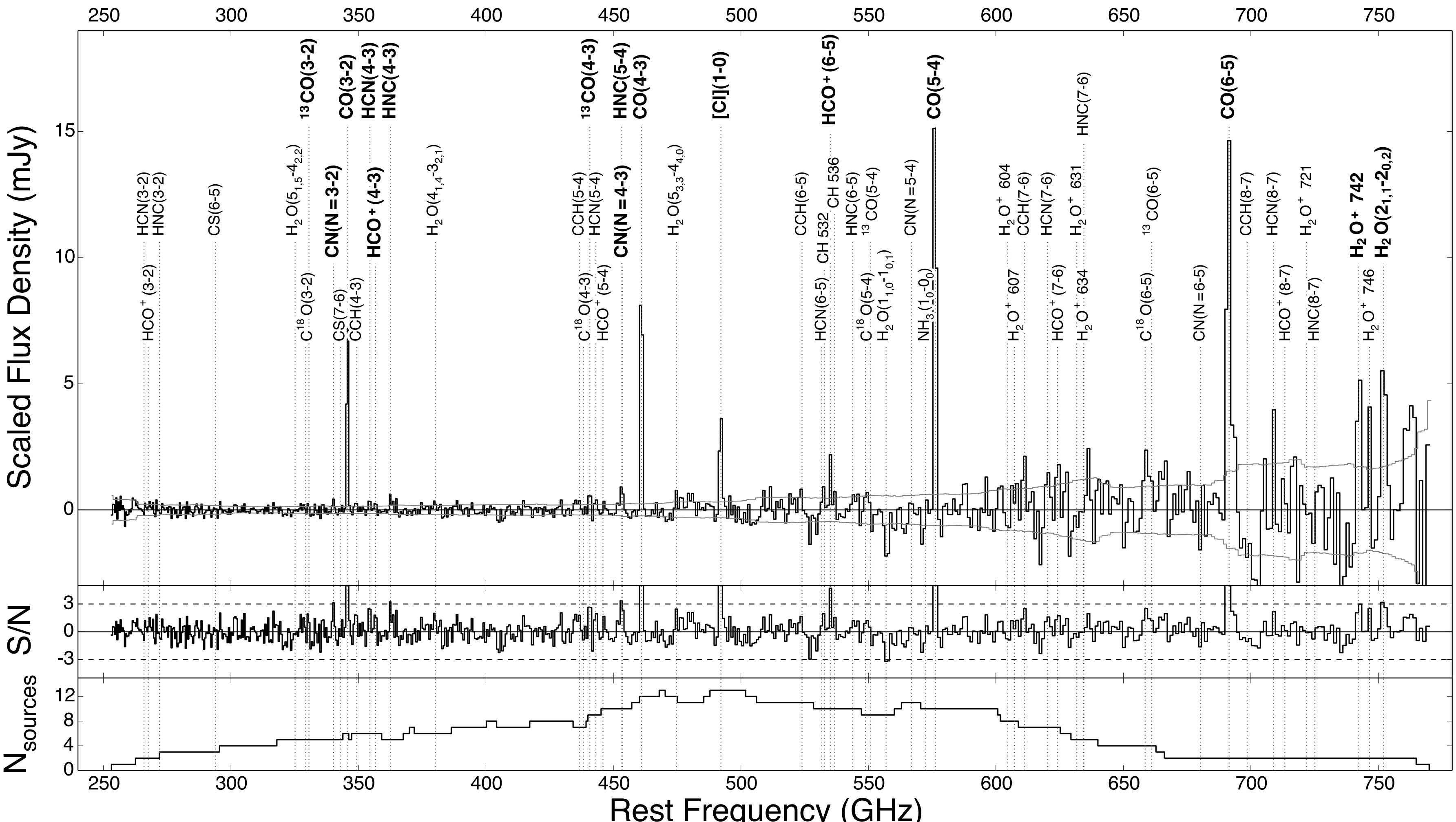


SPT sources:
Occupy an area around $L_{[CII]}/L_{CO(1-0)}$ = 5200 ± 1800.
How can this correlation be explained?

The nature of the [CII] emission

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

Considering three cases:
1. Optically thin [CII] and optically thick CO(1-0)
2. Optically thick [CII] and optically thin CO(1-0)
3. Equal optical depth of [CII] and CO(1-0)



J. Spilker et al. 2014

Considering three cases:

1. Optically thin [CII] and optically thick CO(1-0)
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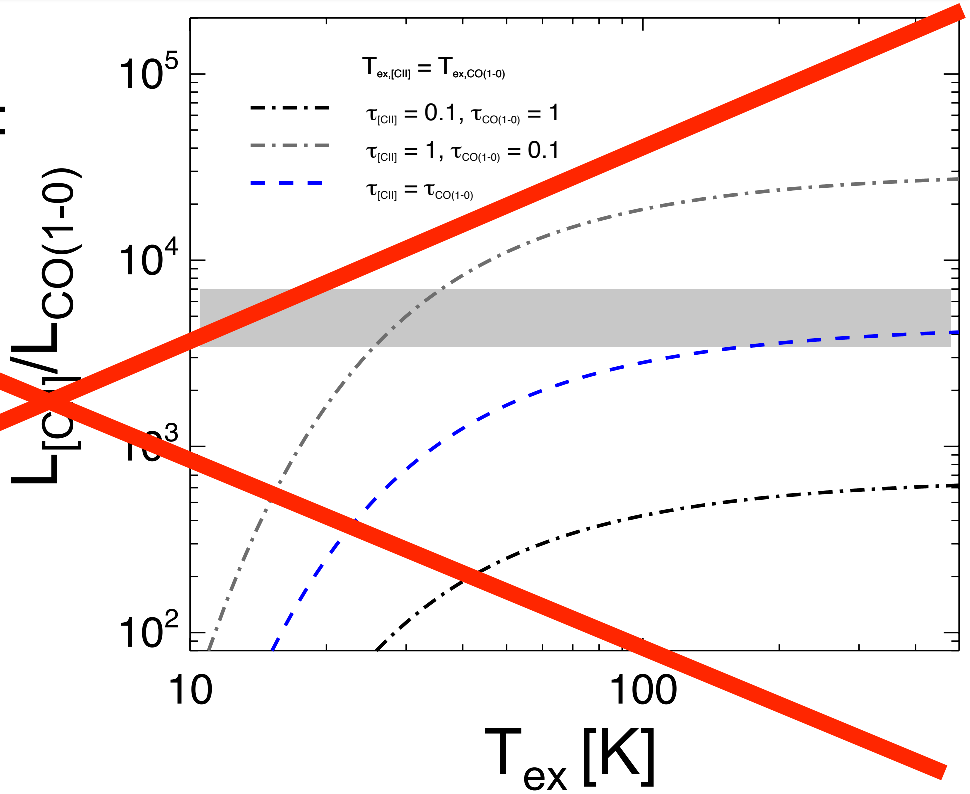
For Equal Excitation Temperatures

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

For equal excitation temperatures:

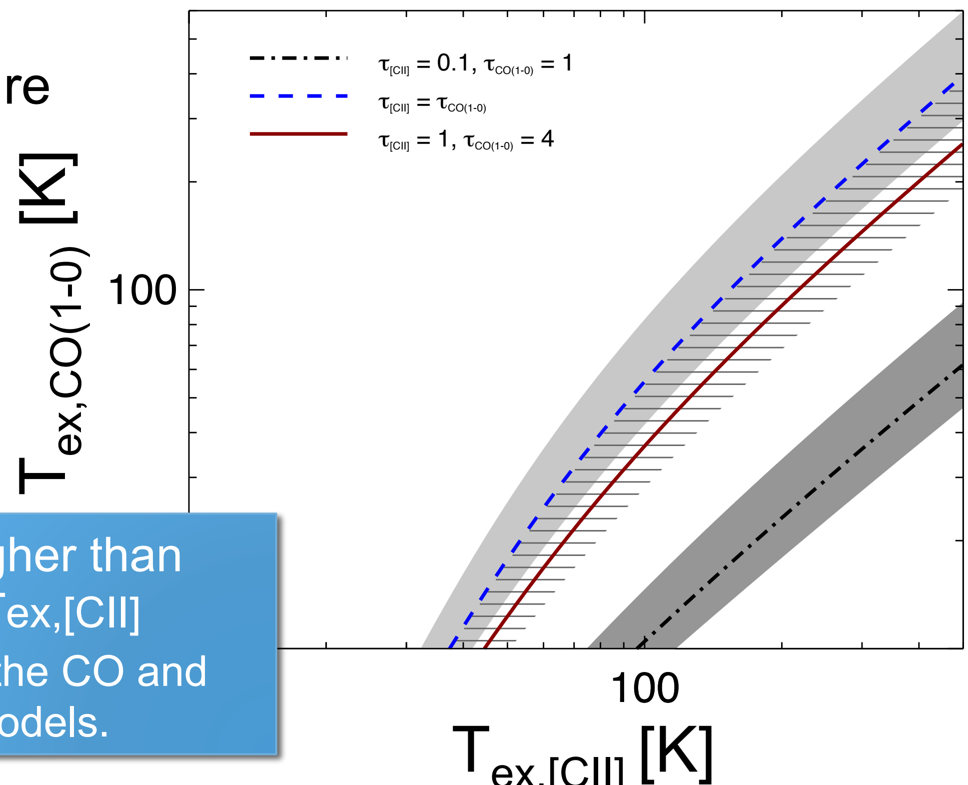
Only for equal optical depth does the luminosity ratio reach the observed range, but only for high Tex



For Different Excitation Temperatures

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

The CO(1-0) excitation temperature as function of the [CII] excitation temperature.



The [CII] excitation temperature is higher than the CO(1-0) excitation temperature: Tex,[CII] >Tex,CO(1-0). Indicating a separation of the CO and [CII] emitting gas similar to simple PDR models.

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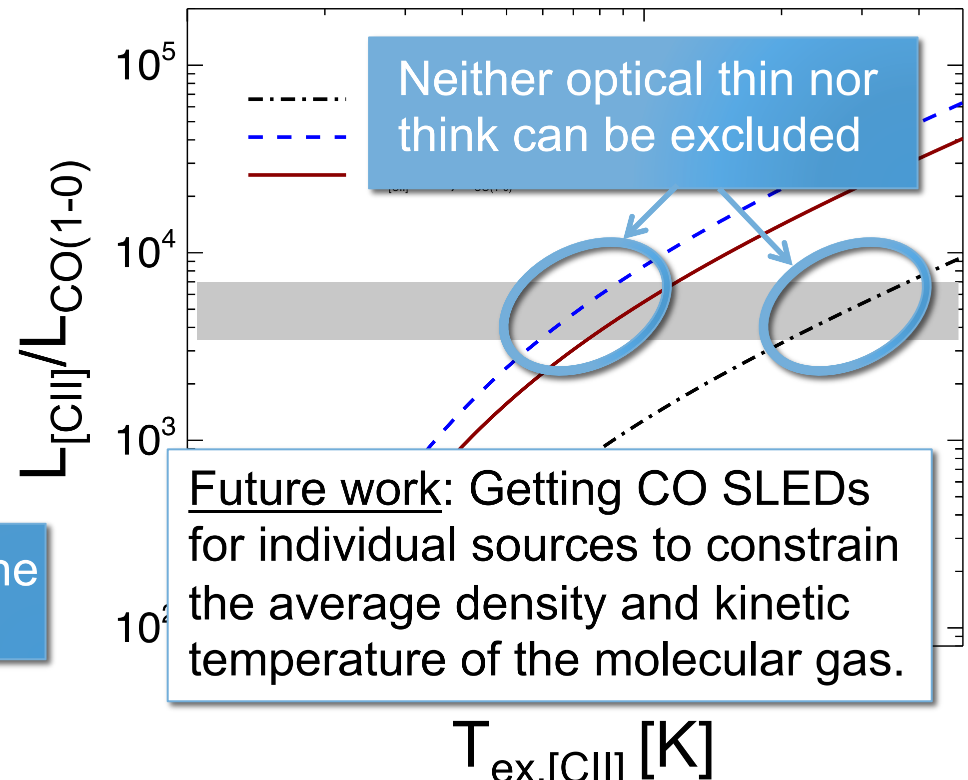
For a fix CO(1-0) excitation temperature of ~ 35K – from CO SLEDs (Spilker et al. 2014)

The luminosity ratio reaches with in the observed range for Tex,[CII]~60-90K



Neither optical thin nor think can be excluded

Future work: Getting CO SLEDs for individual sources to constrain the average density and kinetic temperature of the molecular gas.

Summary

A uniform selected sample of high-z lensed dusty star forming galaxies - making a more reliable comparison between physical condition of the ISM in galaxies over the redshift range z ~ 2 - 5.7 possible.

The lensing of these SPT sources makes it possible to study both the atomic and molecular ISM, via photon dominated regions at high-z.

Bright [CII] lines have been detected for 17/20 sources.
Bright low-J CO lines have been detected for 17/20.
→ 11 sources having both detections of [CII] and low-J CO.

[CII] and ALMA mid – J CO velocity profiles are statistically similar
→ Suggest that the [CII] and CO emission originate from the same regions and that differential lensing is not significant

The SPT DSFGs have a fitted ratio of ~5200±1800, suggesting low to moderate optical depth of [CII] ($\tau \lesssim 1$) and higher excitation temperature of [CII] then CO(1-0). This implies a medium of 'separated' CO(1-0) and [CII] emitting gas ~ similar to the structure for PDR models.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