SEARCH FOR [CII] EMISSION IN z=6.5-11 STAR-FORMING GALAXIES

Gonza’les-Lo’pez et al. 2014 arXiv:2014.3228v1

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Motivation and Background

- 課題研究では high-z galaxy からのミリ波・サブミリ波輝線に興味を持ち延久を進めてきた.
- 課題研究では ALMA archive data を用いてミリ波・サブミリ波の輝線探査を行ない，CO の回転遷移輝線と思われる line を検出することができた.
- また，当初から high-z galaxy における微細構造線の観測にも興味を抱いており ALMA cycle-2 proposal では [OIII] 88 µm 微細構造線の観測を提案した.
- 今後，課題研究ですすめた archive data の解析による blind-line survey に加えて Herschel 分光観測の archive data の解析も考えている.

Abstract

- z > 6.5の LAE とJ-Dropout galaxy で [CII] line を探査した
  - SDFで見つかった LAE 3つ (@z~6.5-7) + lensされたz~11のgalaxy candidate
- それぞれの銀河について [CII] line の upper limit を求めた.
- CMB の影響を考慮して近傍銀河 NGC 6946 の SED template から FIR luminosity の upper limit を求めた.
- この論文ではさらに，high-z [CII] line 探査に関連した様々な状態や将来のALMA・CCAT を用いた high-z [CII] line 探査の困難さを検討している.

1. Introduction

- Lyα 線は z~7 程度までの銀河を見つけるのに有用な輝線であるが，z ≥ 7 となってくると IGM の HI によって吸収されてしまい観測するのが難しくなる．また，その光学的厚さのために Lyα 線の強度や形状から直接ガスの性質を制限するのは困難である.

  => 遠方銀河の研究には Lyα 線以外の輝線を使う必要性.

- [CII] 158 μm line は z>7 での中性 IGM による吸収の影響を受けないうえ非常に明るい輝線である．[CII] line は銀河全体の星形成活動の良いトレーサーである.

- LAE は星形成活動が活発であると考えられており，近年の MIR での観測 (z~2.5, z<0.3)によるとその星形成活動のほとんどがダストに強く覆われていることが分かった (Oteo et al. 2012a,b).

  => LAE は high-z [CII] detection の有力候補である.

2. Observations
2.1. Source Selection

- Three LAEs at SDF

Source	RA	DEC	Redshift	Reference
IOK-1	13:23:59.80	+27:24:56.0	6.965	Iye et al. 2006
SDF J132415.7	13:24:14.70	+27:30:58.0	6.541	Taniguchi et al. 2005
SDF J132498.3	13:24:08.30	+27:15:43.0	6.554	Taniguchi et al. 2005

- Lensed LBG

Source	Redshift	Reference
MACS0647-JD	$10.7^{+0.6}_{-0.4}$	Coe et al. 2013

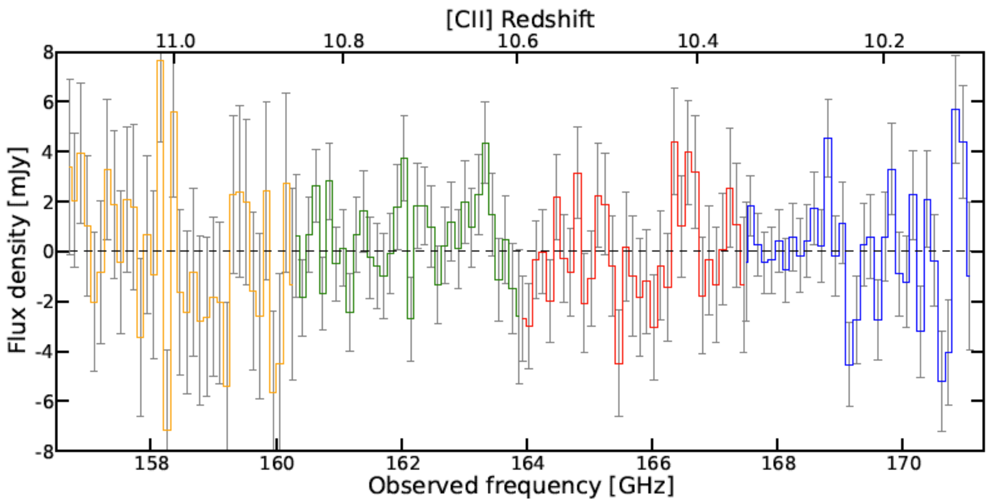
2.2. CARMA Observations
2.3. PdBI Observations

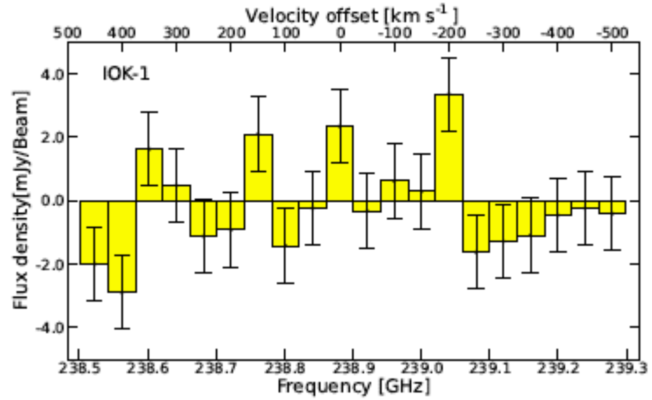
- CARMA Observations
  - Source: Three LAEs
  - Date: Between 2008 July and 2010 July
  - Array configuration: Most compact D and E
  - Tuning: ~150 km/s bluer than expected frequency from the redshift determined by the peak of the Lyα line

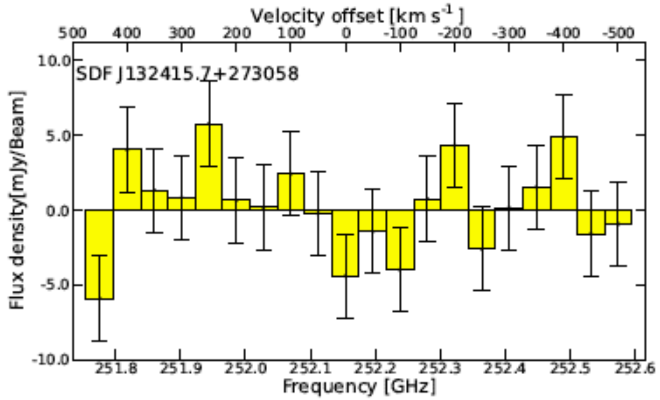
- PdBI Observations
  - Source: Lensed LBG
  - Date: 2012 November
  - Array configuration: C configuration
  - Tuning: 4 WideX frequency set up, covering 80% of photometric redshift range (z=10.1-11.1)
  - Two lensed image (JD1 and JD2) are within 18”

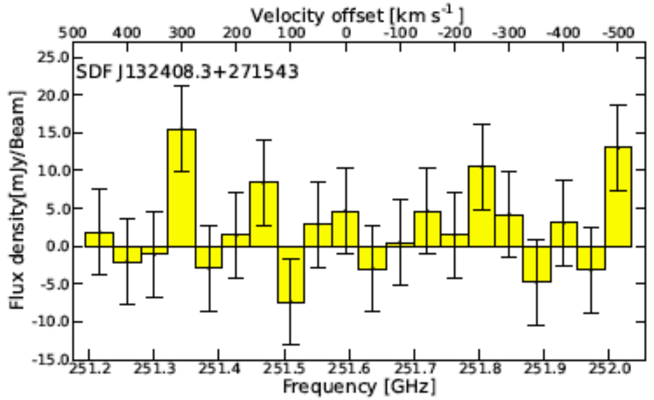
3. Results
3.1. Line emission

- No significant emission is detected at redshifted line frequencies or close to them.
- Channel resolution = 50 km/s, similar to the expected FWHM of the [CII] emission line.
=> see Sect. 4.1 for detail
- The upper limits were estimated assuming that the source were unresolved.
- For LBG, the spectra of the two images were corrected by primary beam pattern before combination .

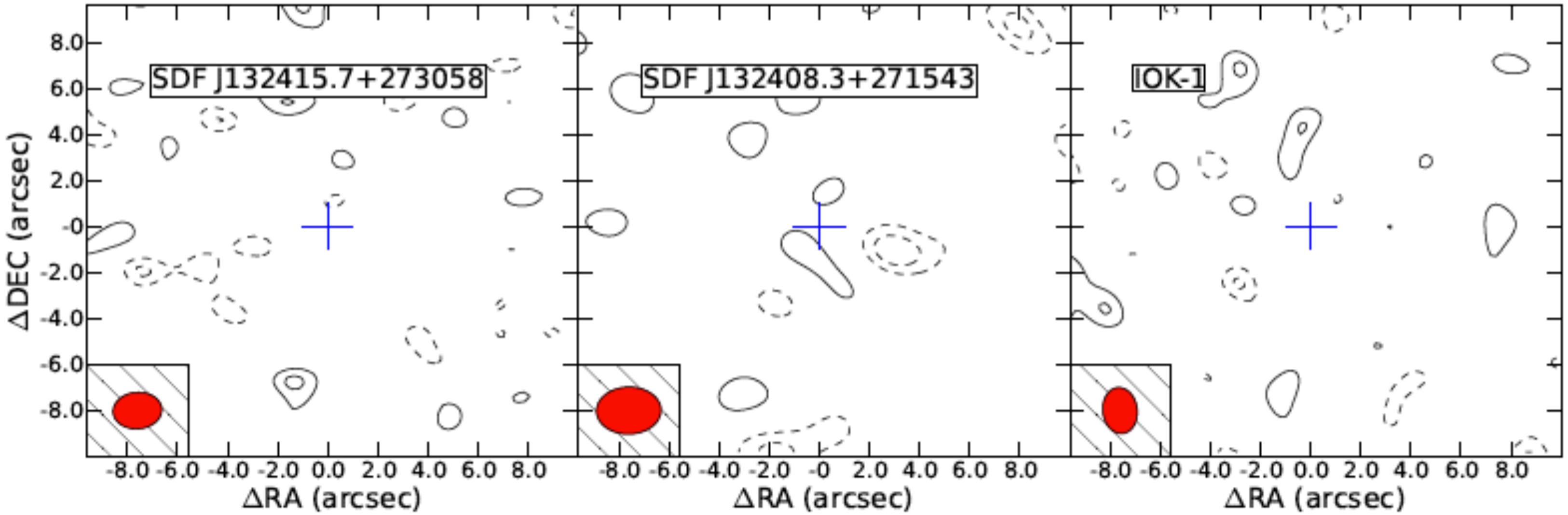




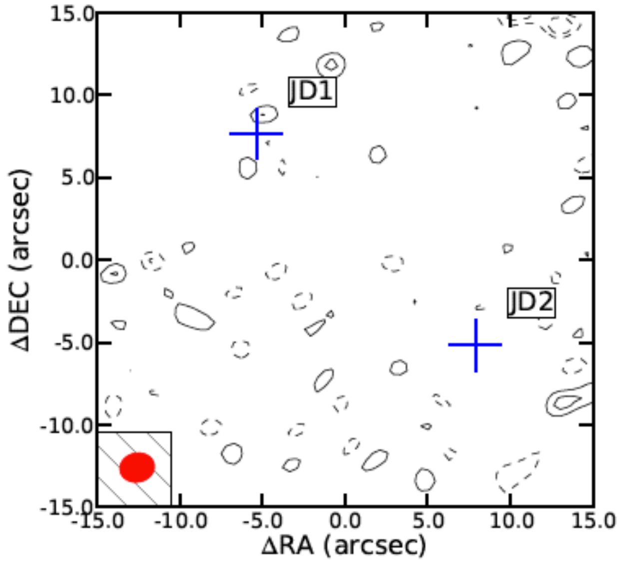




3.2. Continuum Emission



- No continuum emission is detected in the observation of the three LAEs and the z~11 LBG.



3. Results

Table 1
Summary of Observations and Results for the LAEs

source	RA J2000.0	DEC J2000.0	z[a]	ν_{obs}[b] GHz	σ_{cont}[c] mJy b^{-1}	σ_{line}[d] mJy b^{-1}	$L_{[CII]}$[e] 10^8 L$_\odot$	$L_{IR,CMB}^{N6946}$[f] 10^{11} L$_\odot$	$SFR_{dust,CMB}$[g] M$_\odot$ yr^{-1}	SFR_{UV}[h] M$_\odot$ yr^{-1}
IOK–1	13:23:59.80	+27:24:56.0	6.965	238.881	0.19	1.17	<2.05	<6.34	<109.1	∼24
SDF J132415.7	13:24:15.70	+27:30:58.0	6.541	252.154	0.37	2.82	<4.52	<10.3	<177.2	∼34
SDF J132408.3	13:24:08.30	+27:15:43.0	6.554	251.594	0.75	5.67	<10.56	<21.0	<360.9	∼15

Note. — All luminosities upper limits are 3 σ.

Table 2
Summary of Observations and Results for MACS0647JD

Parameter	MACS0647-JD1, JD2
Coordinates (J2000) JD1	06:47:55.731,+70:14:35.76
Coordinates (J2000) JD2	06:47:53.112,+70:14:22.94
μ (JD1+JD2)	~ 15
Redshift	$10.7^{+0.6}_{-0.4}$
UV SFR	~ 1 [M$_\odot$yr^{-1}]
ν	156.7-171.1 [GHz]
σ_{cont} [a]	0.17 mJy b^{-1}
σ_{line} (Setup A)[b]	3.31 mJy b^{-1}
σ_{line} (Setup B)[b]	4.12 mJy b^{-1}
σ_{line} (Setup C)[b]	3.19 mJy b^{-1}
σ_{line} (Setup D)[b]	6.42 mJy b^{-1}
$L_{[CII]}$ (Setup C)[c]	$< 6.78 \times 10^7 \times (\mu/15)^{-1}$ [L$_\odot$]
$L_{[CII]}$ (Setup D)[c]	$< 1.36 \times 10^8 \times (\mu/15)^{-1}$ [L$_\odot$]
$L_{IR}^{N6946,d}$ (Corrected CMB)	$< 1.65 \times 10^{11} \times (\mu/15)^{-1}$ [L$_\odot$]
SFR (L_{IR}) (Corrected CMB)[e]	$< 28 \times (\mu/15)^{-1}$ [M$_\odot$yr^{-1}]
SFR ($L_{[CII]}$) (Setup C)[f]	$< 5 \times (\mu/15)^{-1}$ [M$_\odot$yr^{-1}]
SFR ($L_{[CII]}$) (Setup D)[f]	$< 9 \times (\mu/15)^{-1}$ [M$_\odot$yr^{-1}]

Note. — All luminosities upper limits are 3 σ.

4. Discussion
4.1. Width of the [CII] emission line

- In the previous studies (Walter et al. 2012b; Ouchi et al. 2013), channel resolution is 200 km/s, which is motivated by the width of the Lyα emission.

  => In this paper, they suggest that the [CII] line could be narrower than the previously assumed value.

- [CII] detection on a LAE @ z=4.7 with ALMA (Carilli et al. 2013)
  - FWHM is ~ 56km/s , one order of magnitude narrower than the width of Lyα emission line of 1100 km/s of the same source (Petijean et al. 1996; Ohyama et al. 2004).
  - This LAE is close to the quasar BRI 1202-0725, but this quasar is unlikely the source of heating and ionization in the LAE (Ohyama et a. 2004).
  - In conclusion, this LAE is not different from the general population of LAE and [CII] detection in this LAE can be used as a reference for [CII] searches in other LAEs at high-z.

4.1. Width of the [CII] emission line

- Vallini et al. 2013 simulate the [CII] emission in a halo similar to LAE Himiko @ z=6.6
  - They found that 95% of the [CII] emission is generated in the CNM (but they did not include PDRs => is it fair ?) , mainly in clumps of individual size < 3kpc and FWHM of the main peak is ~50 km/s.
  - The width of [CII] emission is first order determined by the gravitational potential of the clumps.
  - It may occur that emitting clumps moving around the galaxy could combine and produce a broader line. However such behavior is not observed in the simulation.
- They do not discard the possibility of [CII] lines being broader than their assumption, but this appears to be plausible.

4.2. CMB effect

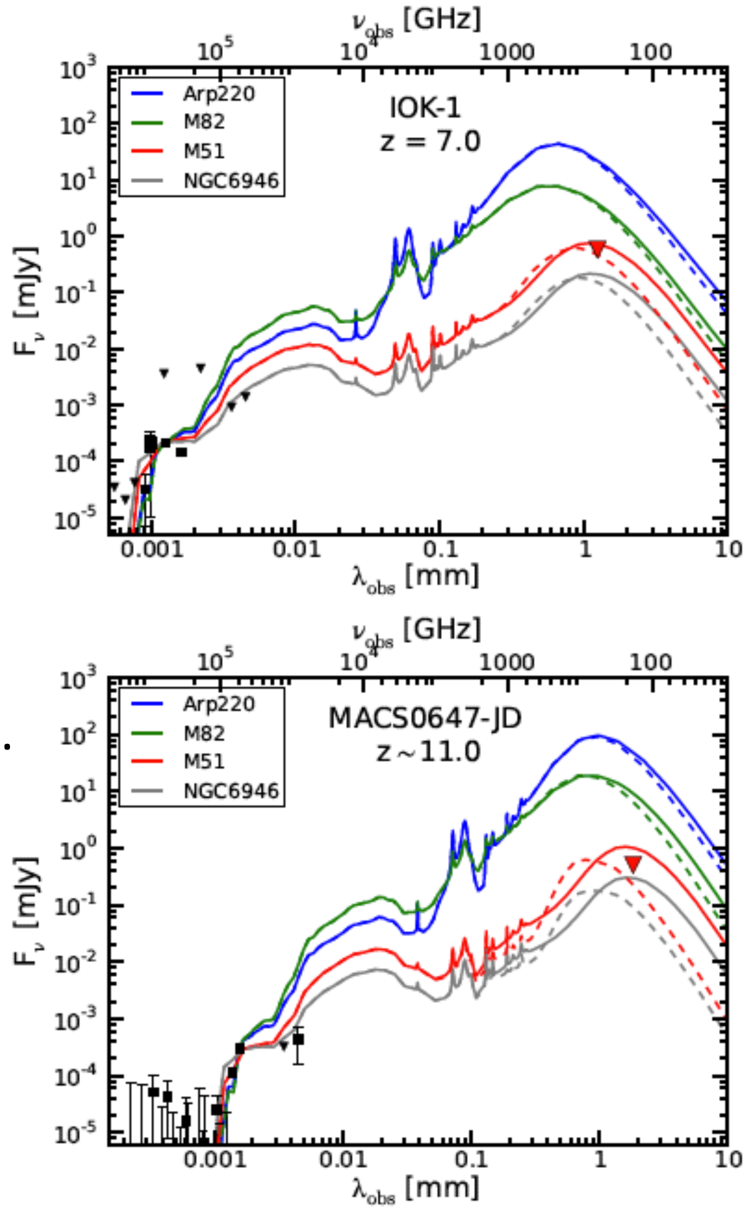
- The CMB become an important factor to take into account for observations of objects at high redshift.

- In this paper, they take into account de Cunha et al. 2013 and get following equation.

$$\frac{F^{\rm obs}_{\nu/(1+z)}}{F^{\rm int}_{\nu/(1+z)}} = M_\nu \left[1 - \frac{B_\nu(T_{\rm CMB}(z))}{B_\nu(T_{\rm dust}(z))}\right]$$

- The CMB effects on the [CII] line observations. However the excited temperature, which is equal to the kinetic temperature is bigger enough than CMB, so observed [CII] flux is similar to the intrinsic flux.

$$\frac{S^{\rm obs}_{\nu/(1+z)}}{S^{\rm int}_{\nu/(1+z)}} = \left[1 - \frac{B_\nu(T_{\rm CMB}(z))}{B_\nu(T_{\rm dust}(z))}\right]$$



4.3. Spectral energy distribution of the galaxies

- They scale the SED of NGC 6946 to the 3 sigma upper limits of the mm observations and integrate from 8 μm to 1mm (rest frame) to compute the IR luminosity (cf. Walter et al. 2012b).

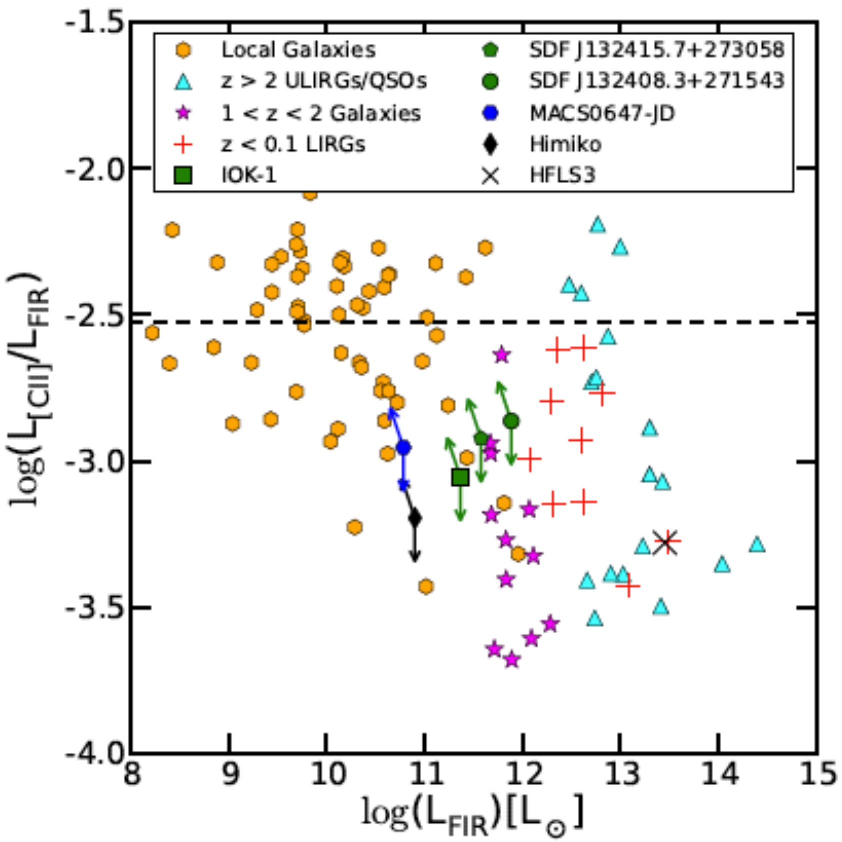
- Estimating the IR luminosity using NGC 6949 without taking into account the CMB result in a significant underestimation of the luminosity upper limits.
  - LAEs @ z~6.6 is 35% higher than without correction. IOK-1 @ z~7 is 50% higher than without correction. MACS0647 is ~3.5 times the IR luminosity limit.

- For galaxies with cold dust temperature (~25 K), the effect of the CMB on the observation is very important at high redshift, but it will not greatly affect the detectability of [CII] emission.

4.4. Ratio L_[CII] / L_FIR

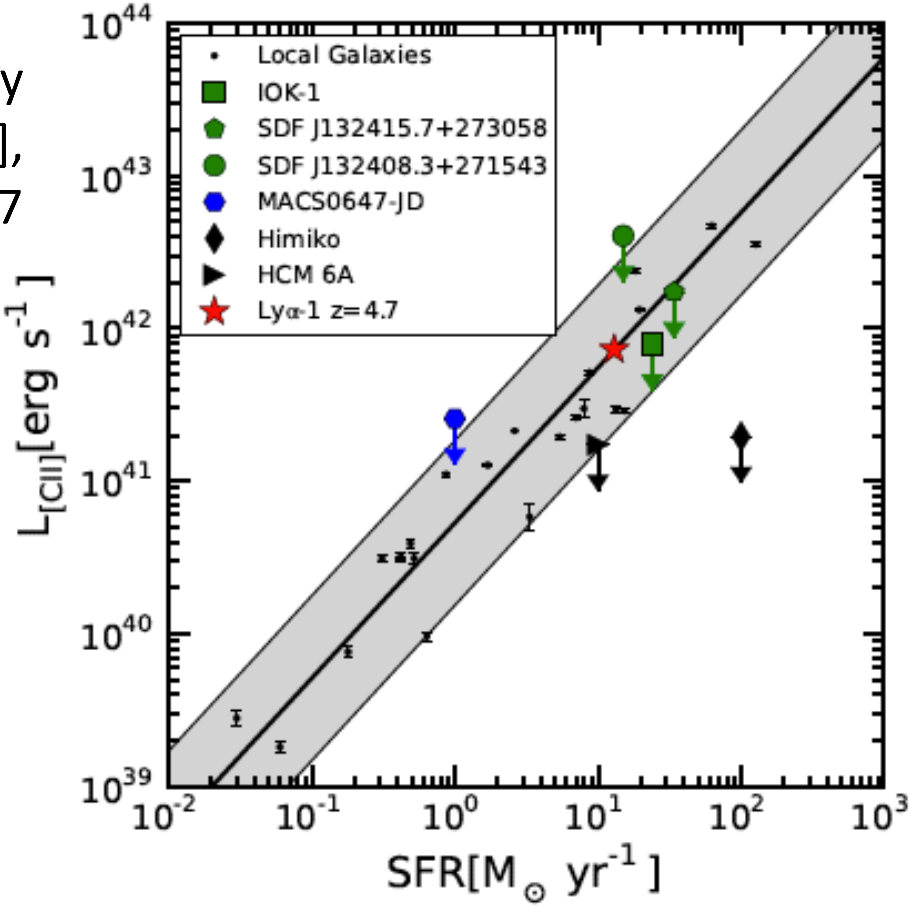
- The ratio L_[CII] / L_FIR is a measure of how efficient the [CII] emission in cooling the gas.
- Different process can affect the ratio.
  - Low metallicity, the fraction of [CII] emission associated with the ionized medium, optical depth @ 158 μm …
- The ratio is decrease as the average dust temperature (Daiz-Santos et al. 2013)
- Dainz-Santos et al. 2013 found correlation between the ratio and luminosity surface density of the mid-IR emitting region.
  - By using this relation, they estimate this ratio.

=> LAEs log(L_[CII]/L_FIR)~-2.5, -2.6, -2.9
LBG log(L_[CII]/L_FIR)~ -3.2



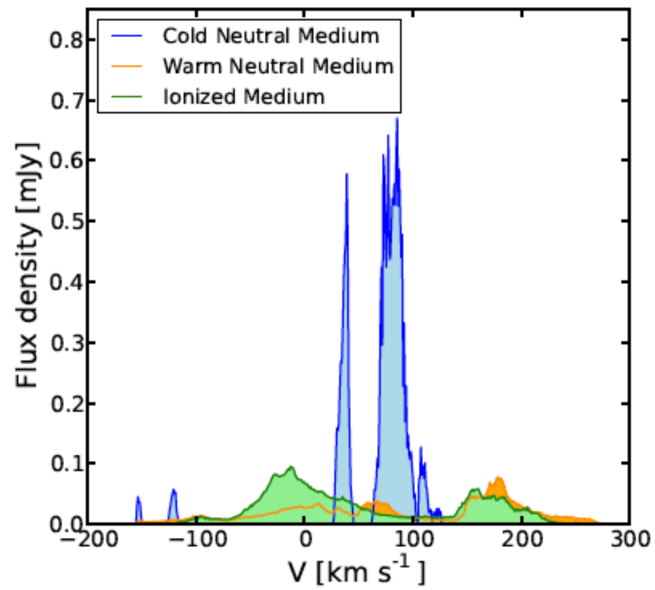
4.5. SFR – L_[CII] relation

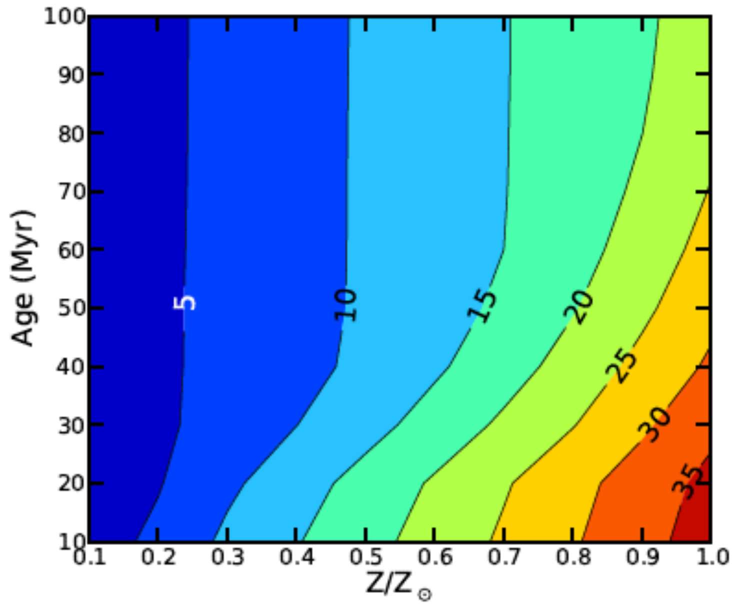
- Their upper limits for the [CII] luminosity fall within the scatter of the SFR - L_[CII], with the exception of SDF J132408.3+27 1543 (and MACS0647JD ?).
- Past observations suggest that LAE @ z>6 could fall bellow the relation found at low-z.
  => More observations are needed



4.6. IOK-1 Models

- Using the same procedure presented in Vallini et al. 2013, they estimate the emission of [CII] for IOK-1 @ z~7.
  - SFR=20 M_sun/yr, stellar population age =10 Myr, Z=Z_sun
- This simulation does not include the emission from PDRs and should be seen as a lower limit.
- Most of the [CII] emission comes from CNM, and FWHM of the main peak is ~50 km/s.
- They present the integrated flux of [CII] for different combination of metallicities and stellar population ages.
  => Strong dependency on metallicity.
- There is the dependency of stellar population ages.





4.7. Spectral resolution
4.8. Atomic mass Estimation

- For a Gaussian emission line, with a FWHM of 50 km/s observed at a channel resolution of 200 km/s, significantly diluted.
  - They will recover 38% of the peak flux of the line at a channel resolution of 200 km/s, and 97% at a channel resolution of 10 km/s.

- They use Equation 1 from Hailey-Dunsheath et al. 2010 to get upper limits to the atomic mass associate with PDRs.

$$\frac{M_a}{M_\odot} = 0.77 \left(\frac{0.7\, L_{[\mathrm{C\,II}]}}{L_\odot} \right) \left(\frac{1.4 \times 10^{-4}}{X_{\mathrm{C}^+}} \right) \times \frac{1 + 2\exp(-91\,\mathrm{K}/T) + n_{\mathrm{crit}}/n}{2\exp(-91\,\mathrm{K}/T)},$$

  - IOK-1 ≤ 2e8 M_sun, J132415 ≤ 4e8 M_sun, J132408 ≤ 1e9 M_sun, MACS0647 ≤ 6e7 M_sun

  - They assume that **all [CII] would arise from PDRs** !

5. Summary and outlook

- They have presented a search for [CII] emission in three LAEs and in a LBG.

1. They have not detected [CII] emission line any of our targets.

2. No detection of the FIR continuum is found at a wavelength of 158 μm rest frame.

3. The simulations suggest that the [CII] line has a width of the order of 50 km/s.

4. The CMB effect must to be taken into account in attempts to detect FIR continuum in high-z galaxies.

5. Detecting [CII] line in high-z galaxies is difficult even with ALMA. We should first try to detect [CII] in the LAEs with the highest metallicity (?). LBG with Lyα detection may be ideal targets for [CII] searches at high-z.

終わりに…

- High-z star-forming galaxy における [CII] 観測で考慮すべき点が過去の観測やシミュレーションを例にまとめられており，今後そういった観測をする際の参考になると感じた.

- この論文によると，high-z star-forming galaxy で [CII] line の FWHM は~50 km/s と狭くなっているので検出には非常に細かい速度分解能が必要になってくる，と述べられている.

  => [OIII] 88 μm line は high-z star-forming galaxy 観測において [CII] line に取って代わりうるポテンシャルがあるのでは？

  - [OIII] は完全に電離した領域から放出されるので CNM clump からの放射が支配的な [CII] よりも FWHM が広いのではないか(cf. fig. 8)？
  - High-z では [OIII] line が強く観測される可能性がある (Inoue et al. 2014).
  - [OIII] で制限できる物理量としては例えば電離ガスの質量がある (Ferkinhoff et al. 2010).