ALMA follow-up for a z=3.3 DLA found in a galaxy sight-line

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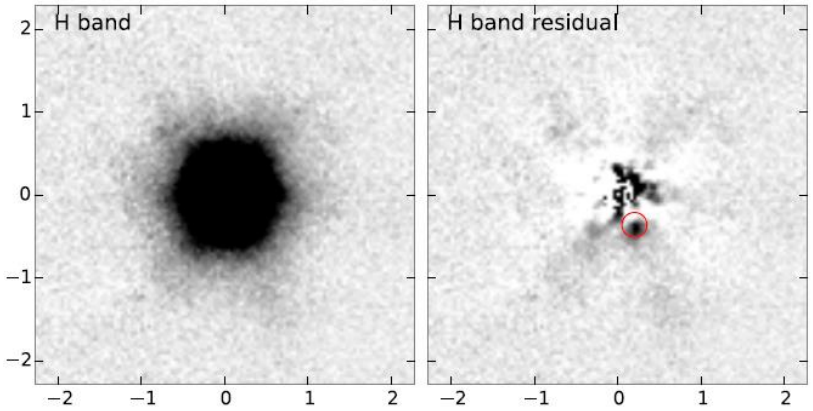
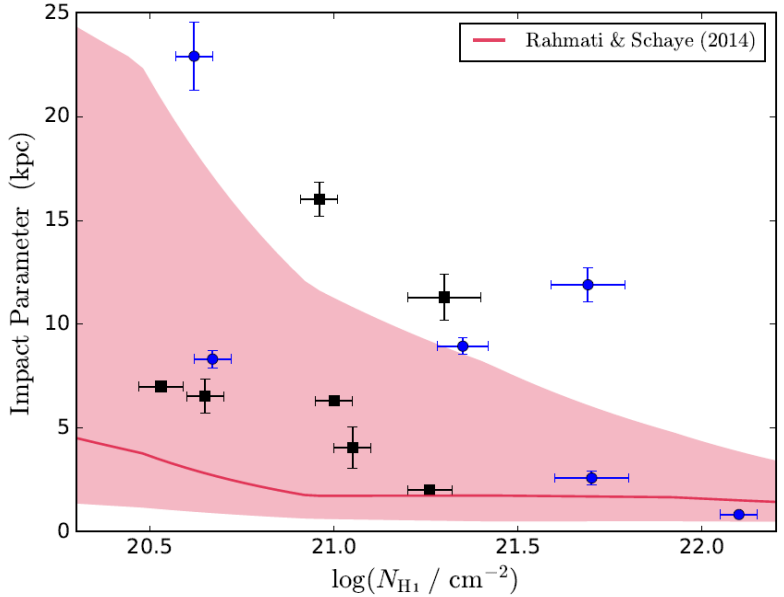
Introduction

- Damped Ly α systems (DLAs) are high HI column density systems found in spectra of bright background sources such as QSOs and Gamma-Ray Burst afterglows.
  - log10(NHI/cm2)>20.3
  - Very important gas reservoirs in the Universe.
- Optical searches for counterparts of DLAs are difficult.
  - Due to the brightness of background QSOs (e.g., Krogager et al. 2017)
  - ~10 optical counterparts were reported.

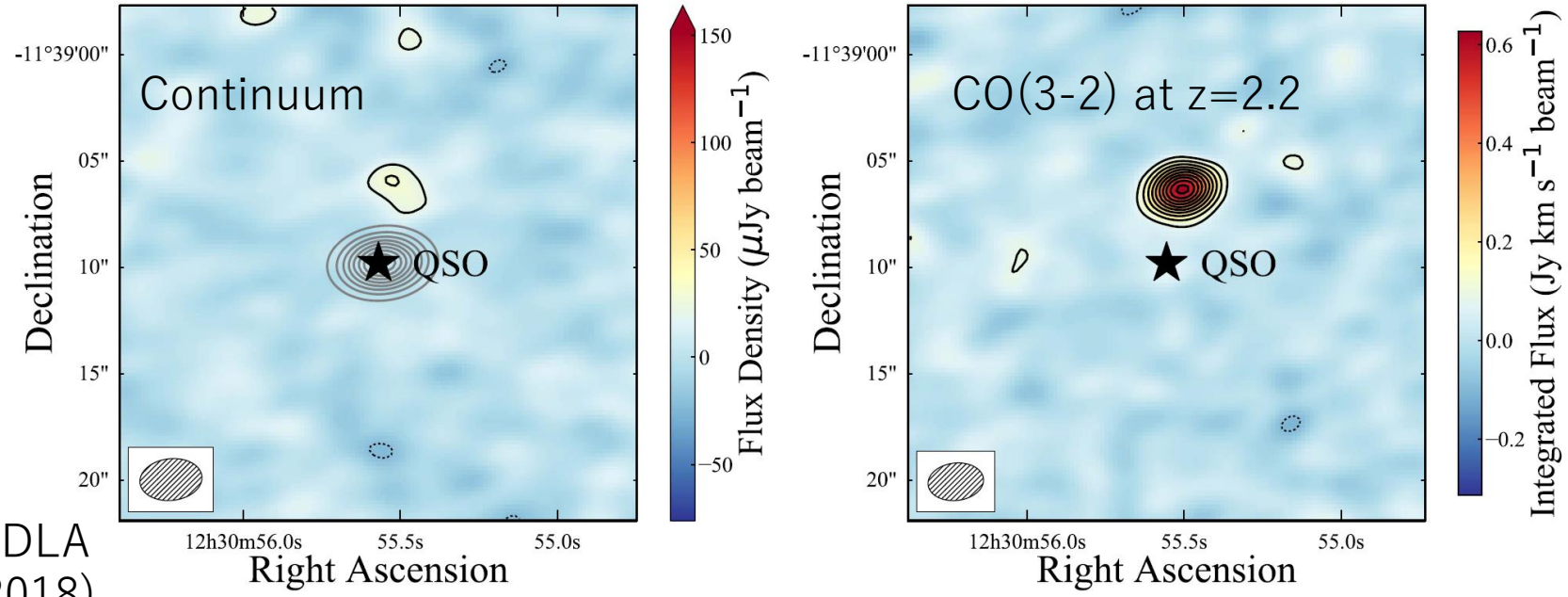


Krogager et al. 2016: Keck AO image (H-band)



Introduction

- ALMA surveys of emission line counterparts of DLAs are yielding very successful results.
  - [CII] 158 line and dust continuum at z~4 (Neeleman et al. 2017; but see Ogura et al. 2020 for a z~3 low-metallicity DLA case)
  - CO and dust continuum at z~0.3, 0.7 and 2 (Møller et al. 2018; Kaneker et al. 2018; Fynbo et al. 2018; Neeleman et al. 2018; Peroux et al. 2019)



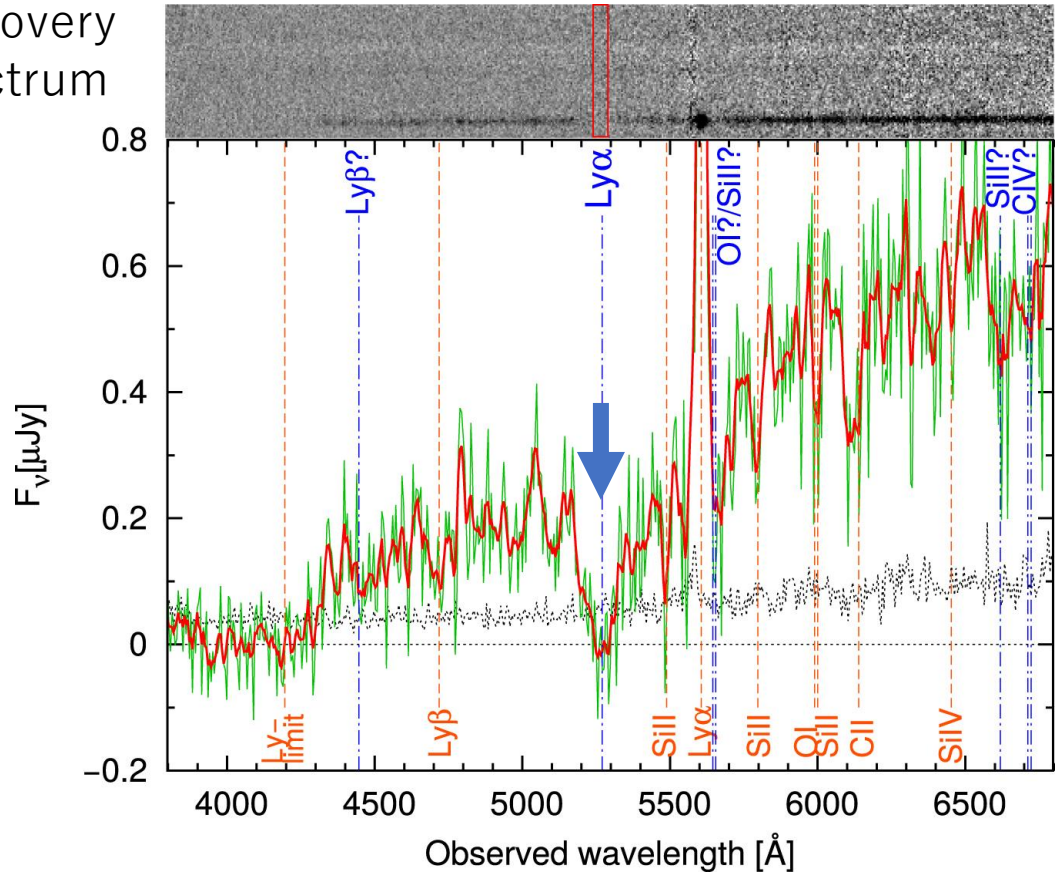
A high-metallicity DLA (Neeleman et al. 2018)

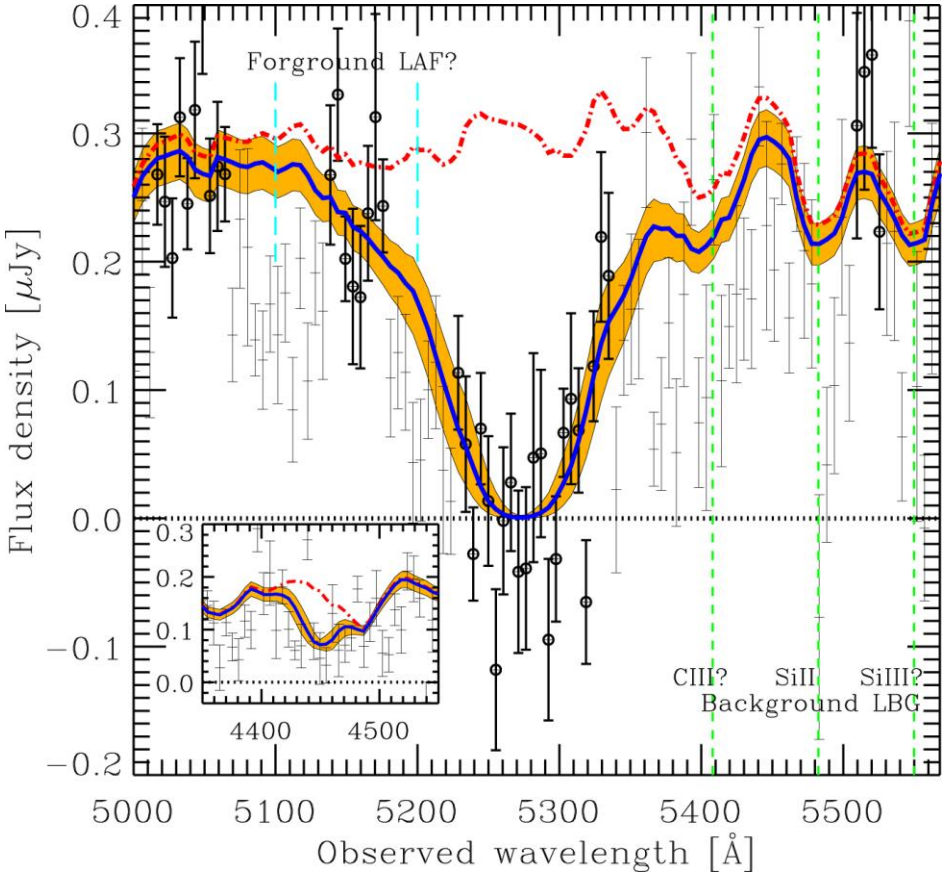
Target

Second example as a DLA found in galaxy spectra.

- DLA found in the spectrum of a Lyman break galaxy in the SSA22 field (Mawatari et al. 2016)
- z(DLA)=3.335, log10(NHI/cm2)=21.68, z(bkLBG)=3.604

Discovery spectrum



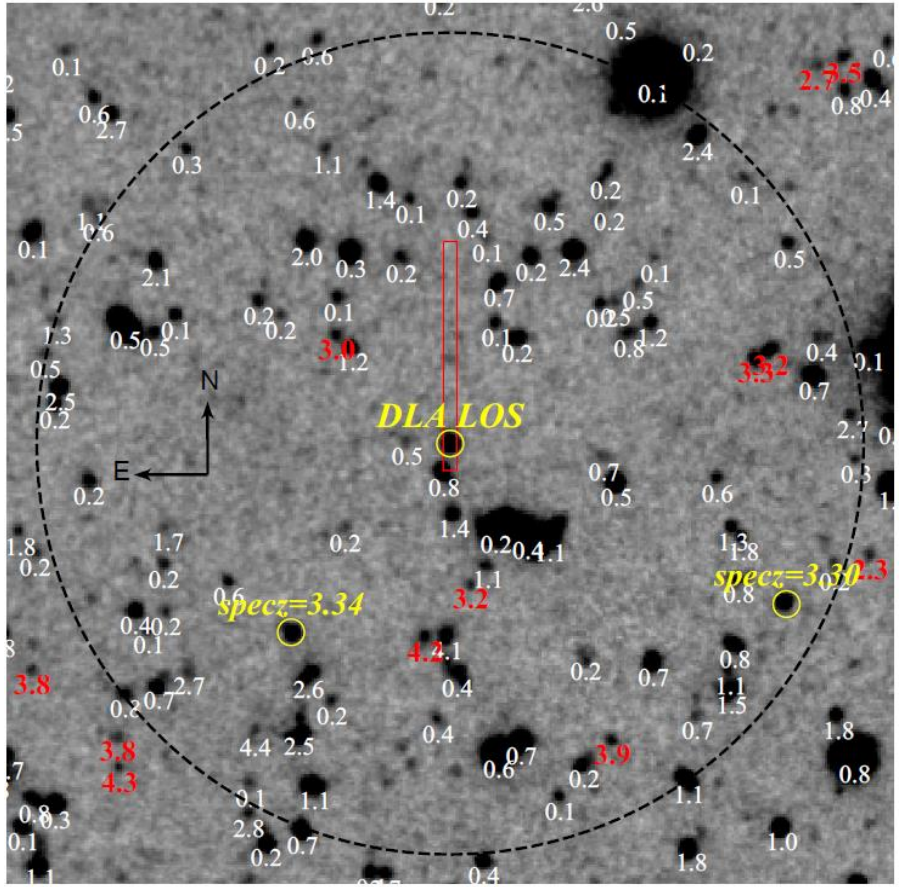


Close-up spectrum of the DLA

Observations

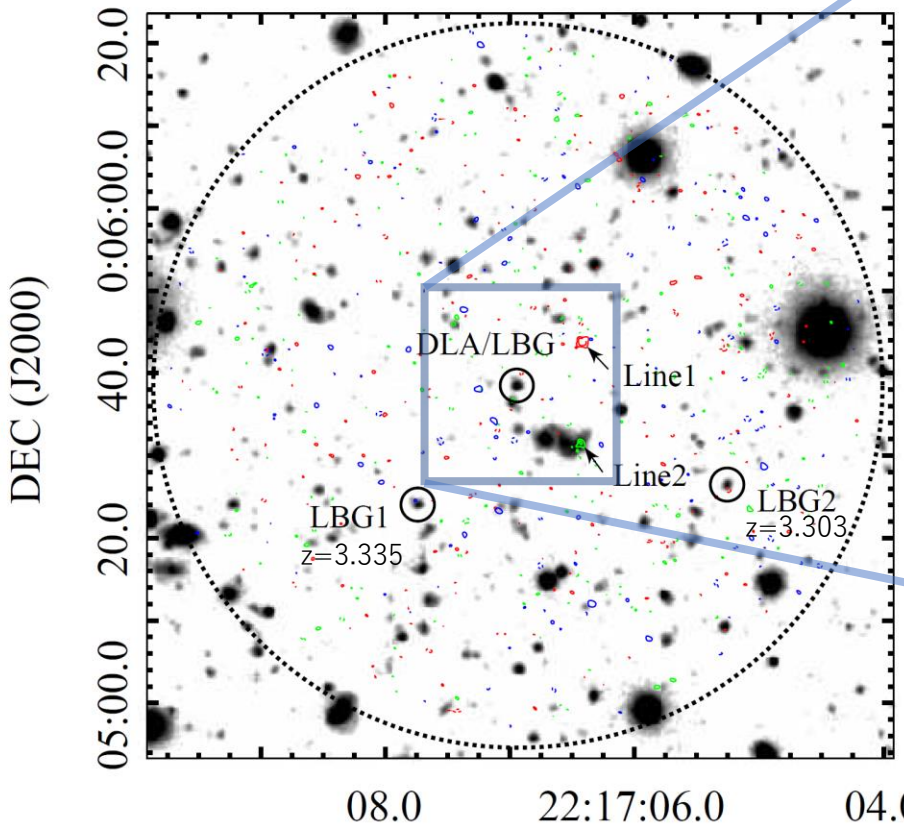
- ALMA Cycle 6: 2018.1.01427.S [Grade C]
- Band 3
  - CO(4-3) at z=3.335 → **106.353 GHz**
  - [CI](1-0) at z=3.604 → **106.898 GHz**
    - **SPW0: 107.000 GHz, 1.875 GHz, 480 channels**
    - **SPW1: 105.200 GHz, 1.875 GHz, 480 channels**
    - SPW2: 95.000 GHz, 1.875 GHz, 480 channels
    - SPW3: 93.200 GHz, 1.875 GHz, 480 channels
- Dates
  - 2018-10-23 (x2), 2018-10-24, 2018-11-05
- Exposure time
  - 3,878 sec + 3,876 sec + 3,876 sec + 3,894 sec = 15,524 sec = **4.3 hours**
- CASA version
  - 5.4.0-68 Pipeline 42030M (Pipeline-CASA54-P1-B)

Dashed circle: Band 3 field-of-view
(Half-maximum of the primary beam)



Results

- **2 emission line detections**
- No continuum detection



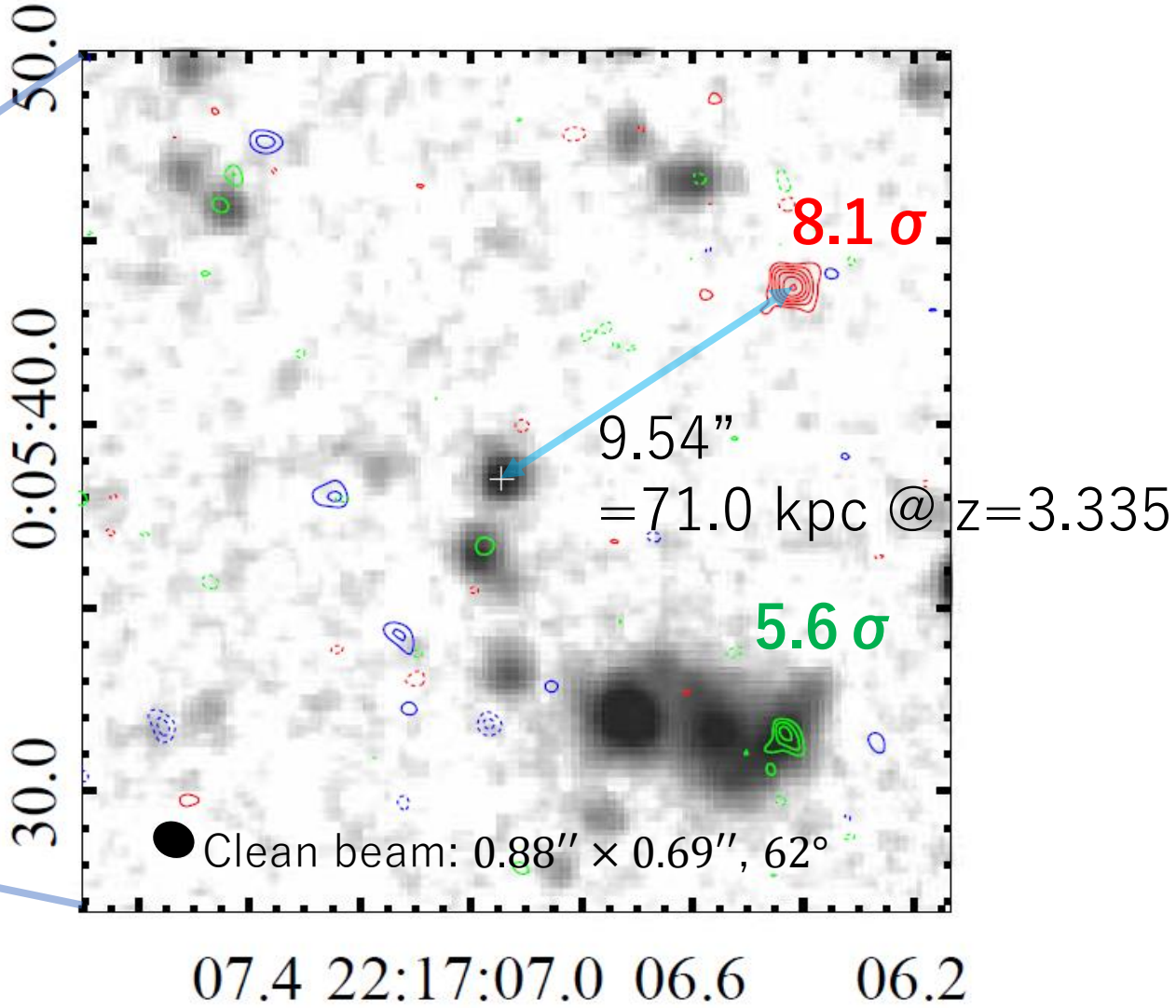


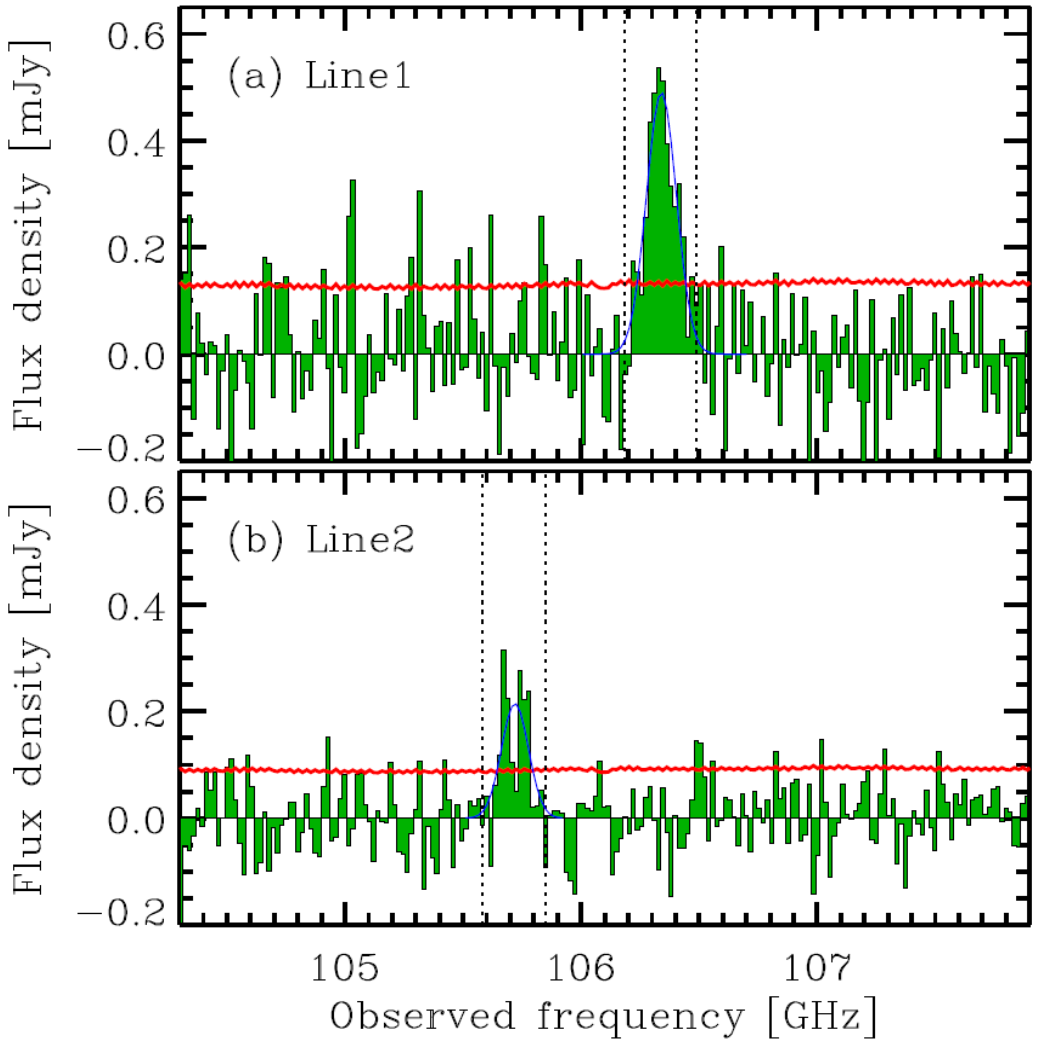
Image: S-Cam i’-band
Dotted circle: 20% sensitivity of PB

Contours: S/N=-4, -3, 3, 4, 5, 6, 7, and 8 σ
Red: Line image (106.186-106.487 GHz)
Green: Line image (105.583-105.849 GHz)
Blue: Continuum at 100.092 GHz

Inoue et al. in prep.

Results

- Spectra



SSA22-B3-Line1		
RA (J2000)	22:17:06.413 ± 0.007	
DEC (J2000)	+00:05:43.74 ± 0.09	
Line center frequency	106.3399 ± 0.0069	GHz
Line FWHM	421 ± 46	km s^{-1}
Peak intensity[a]	0.152 ± 0.019	Jy km s^{-1} beam^{-1}
Integrated flux[a]	0.453 ± 0.087	Jy km s^{-1}
Major axis FWHM[b]	1.56 ± 0.35	arcsec
Minor axis FWHM[b]	0.96 ± 0.30	arcsec
Position angle[b]	125 ± 26	degree
Continuum intensity[c]	< 15 (3-σ)	μJy beam^{-1}
SSA22-B3-Line2		
RA (J2000)	22:17:06.427 ± 0.013	
DEC (J2000)	+00:05:31.32 ± 0.14	
Line center frequency	105.720 ± 0.013	GHz
Line FWHM	380 ± 87	km s^{-1}
Peak intensity[a]	0.100 ± 0.018	Jy km s^{-1} beam^{-1}
Integrated flux[a]	0.279 ± 0.081	Jy km s^{-1}
Major axis FWHM[b]	1.78 ± 0.60	arcsec
Minor axis FWHM[b]	0.80 ± 0.53	arcsec
Position angle[b]	124 ± 26	degree
Continuum intensity[c]	< 16 (3-σ)	μJy beam^{-1}

[a] Primary beam correction has been applied.
[b] Measurements deconvolved from the clean beam.
[c] At the mean frequency of 100.092 GHz. Primary beam corrected.

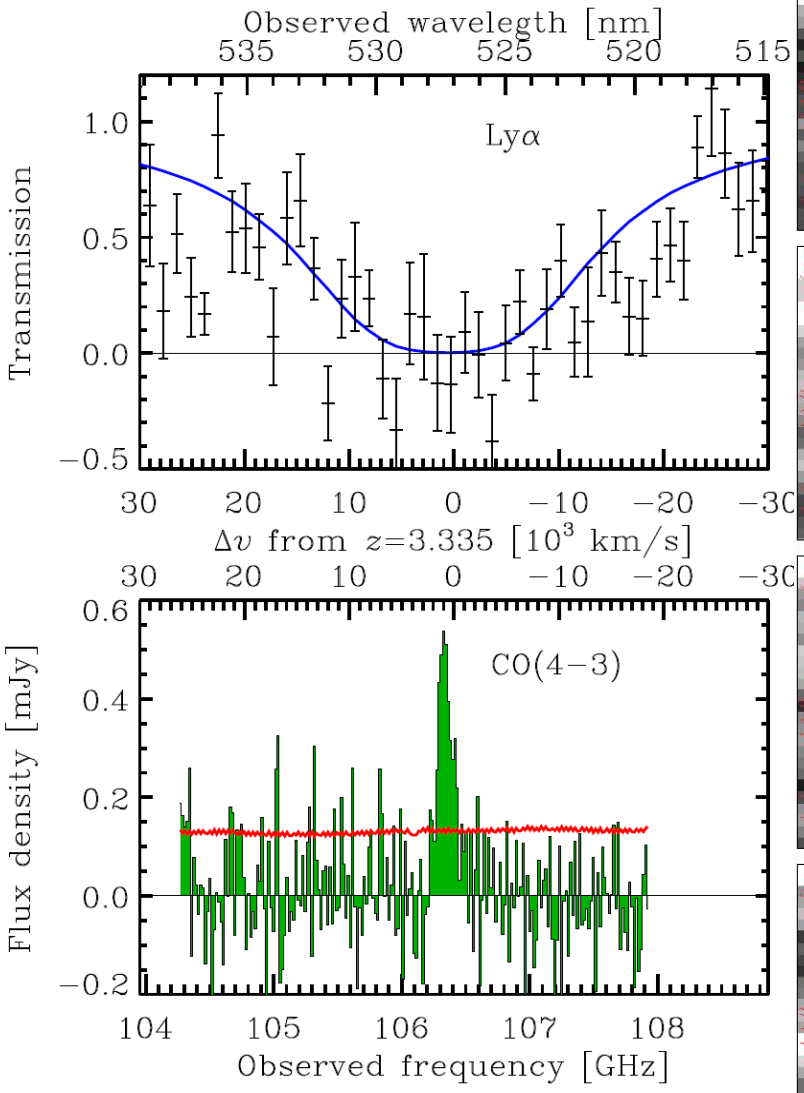
Inoue et al. in prep.

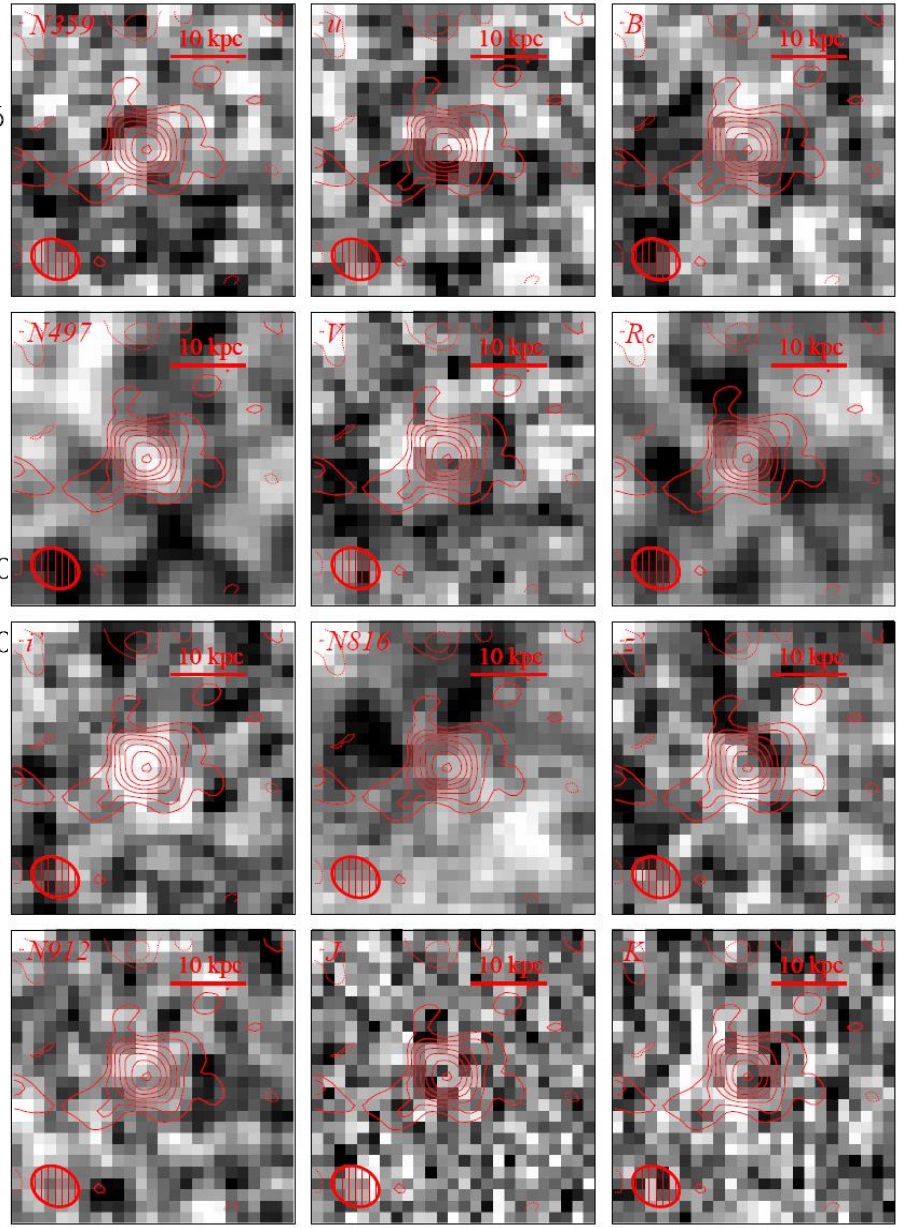
Discussions

SSA22-B3-Line1

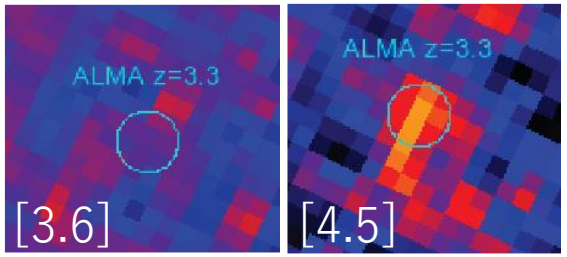
- No continuum counterpart.
  - But, Spitzer/IRAC ch2 [4.5]
- If the emission line at 106.340 GHz is CO(4-3), the redshift is 3.33554.
  - **+160 km/s** from Ly α absorption
- Physical distance is **71.0 kpc** from the DLA sight-line.
  - >2x further than Neeleman+19 CO counterpart at z~2.
- CO(4-3) luminosity corresponds to H2 mass of **3.3e11 Msun**.
  - MW values of $\alpha_{CO} = 4.3$, $r_{41} = 0.17$ are assumed.

Inoue et al. in prep.





Discussions



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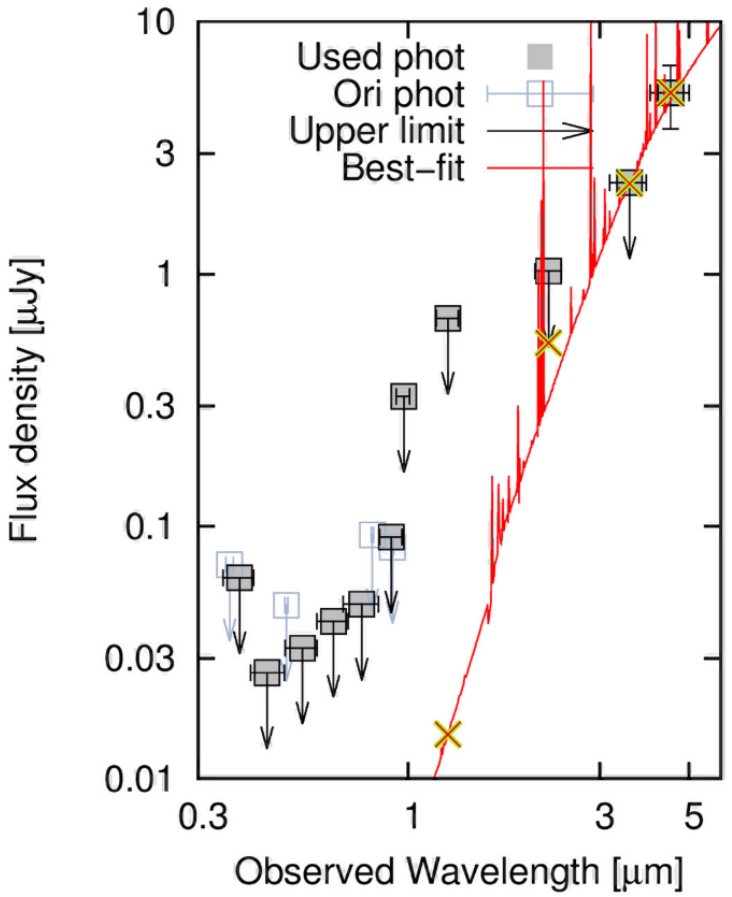
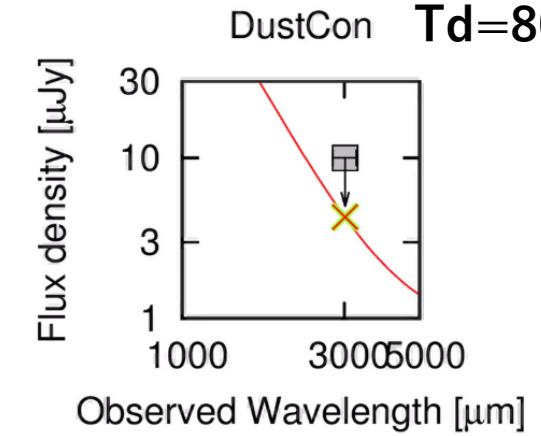
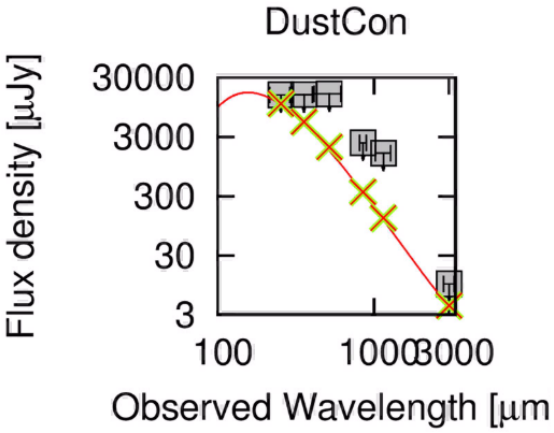




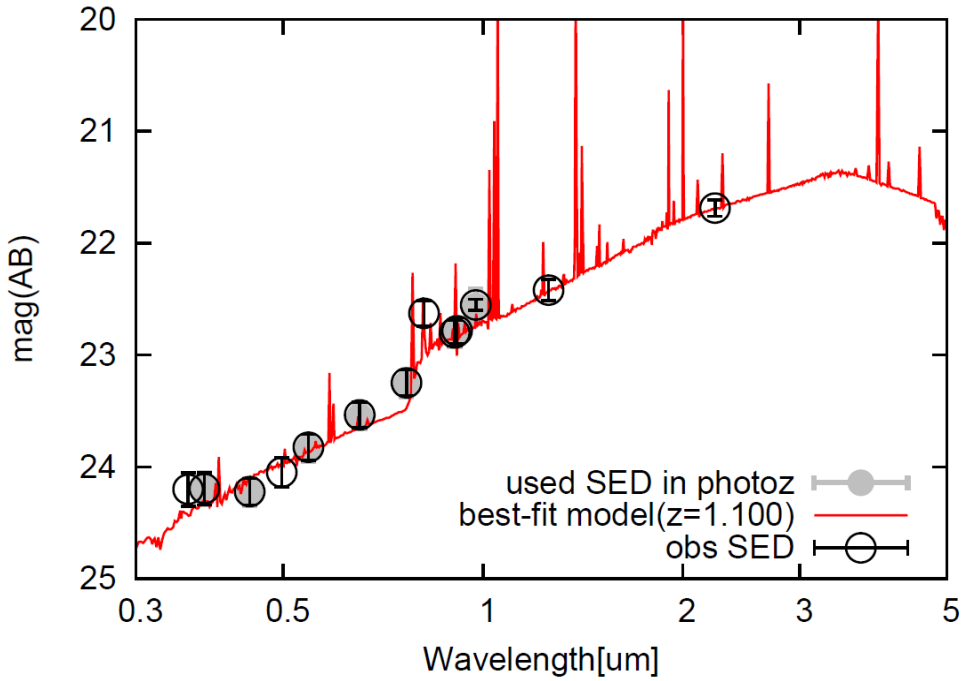


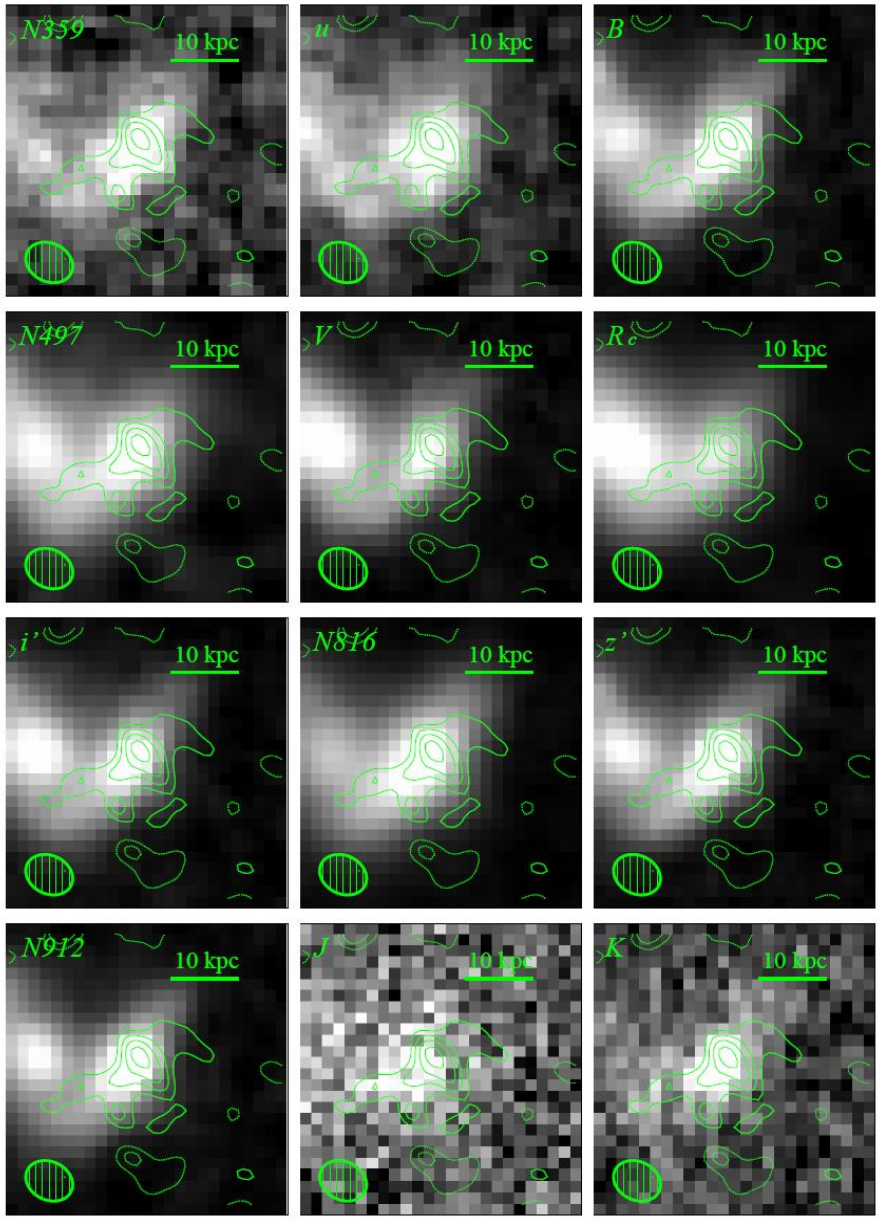
An SMG with **SFR~1000 Msun/yr**

Discussions

SSA22-B3-Line2

- The spatially coincided galaxy has z(photo)=1.1.
- If the emission line at 105.720 GHz is CO(2-1), z=1.18065.
- Probably, this is a **CO(2-1) line at z=1.18**.
- The H2 mass is estimated at **4.4e10 Msun**.
  - MW conversion factors: $\alpha_{CO} = 4.3, r_{21} = 0.50$.





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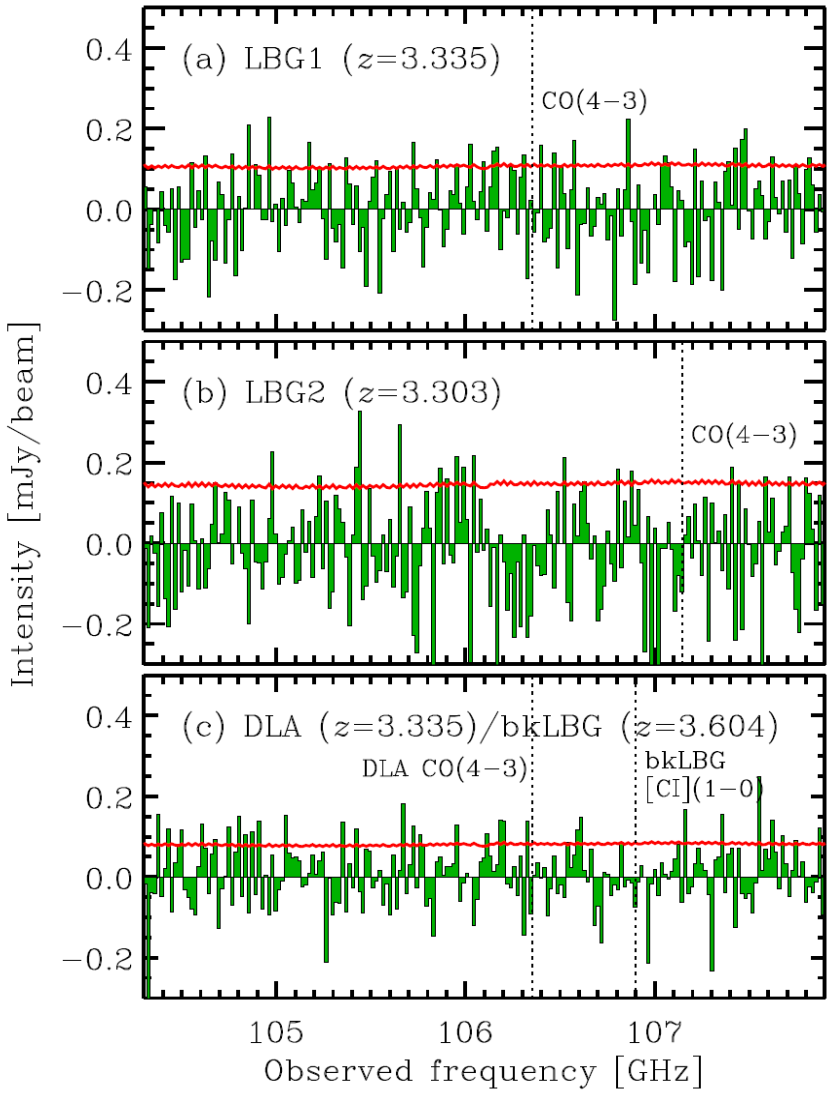
Discussions

CO(4-3) and [CI](1-0) upper limits for LBGs

- LBG1
  - L'CO(4-3)<1.5e9 K km/s pc2
  - M(H2)<3.8e10 Msun
- LBG2
  - L'CO(4-3)<2.1e9 K km/s pc2
  - M(H2)<5.3e10 Msun
- bkLBG
  - L'[CI](1-0)<1.1e9 K km/s pc2
  - M(H2)<5e10 Msun
- DLA
  - L'CO(4-3)<1.2e9 K km/s pc2
  - M(H2)<3e10 Msun
  - N(H2)<5e22 cm-2 c.f. N(HI)=4.8e21 cm-2

  → f(H2)=2N(H2)/[2N(H2)+N(HI)]<0.95



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Discussions

SSA22-B3-Line1

- The most likely solution: SMG at z=3.335
  - Gas-rich (~3e11 Msun)
  - High SFR (~1e3 Msun/yr)
  - Very warm dust (Td~80K)

DLA

- A part of the cosmic web connecting the LBG and the SMG (Line1)?
- The SMG may be located at the node of two filaments?

To confirm the possible cosmic web filaments, Lyα imaging is highly desirable.

A proposal was rejected by ESO...

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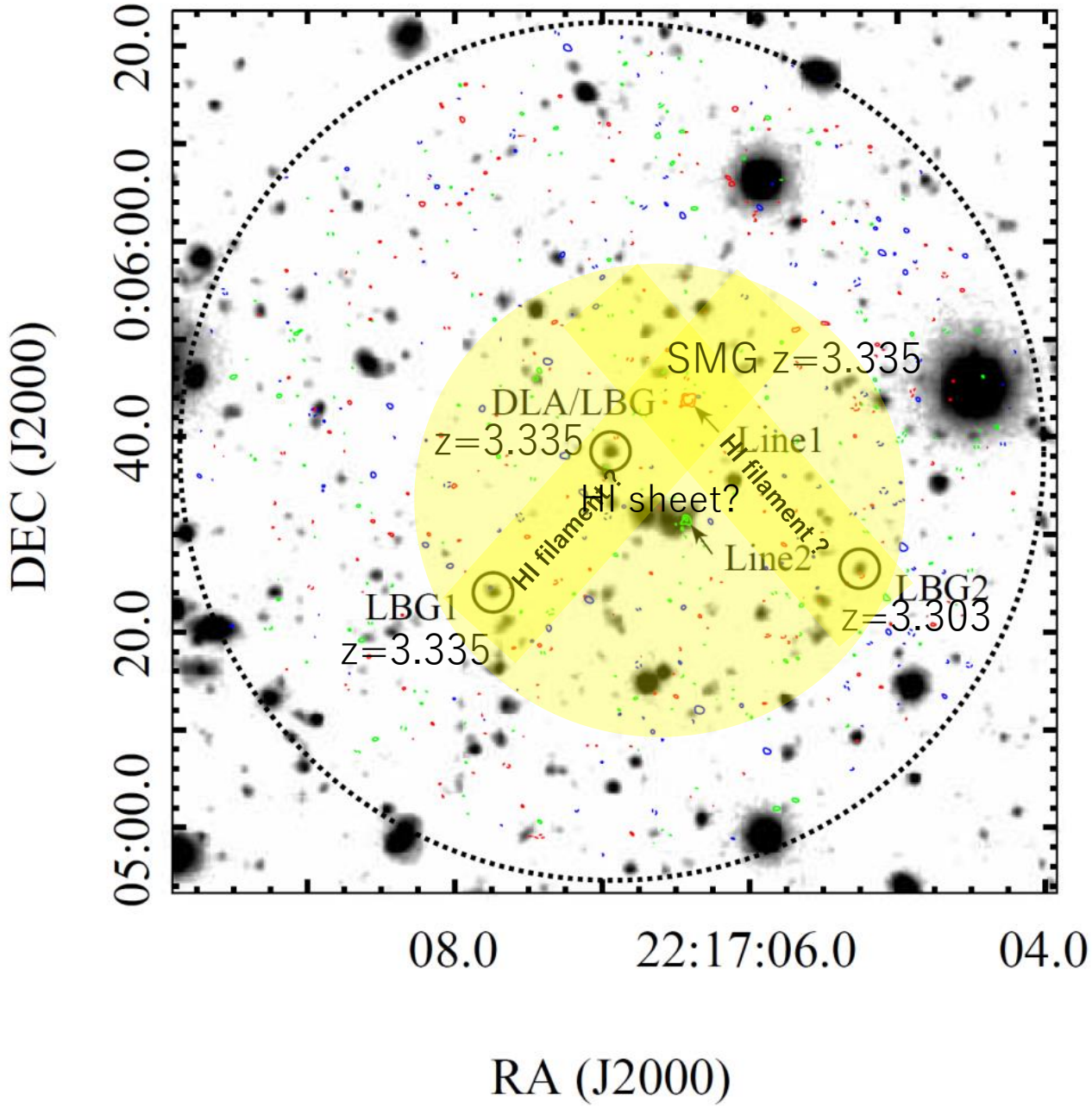

Summary

- We carried out ALMA Band3 observations for a CO(4-3) emission counterpart of a z=3.335 DLA found in an LBG spectrum.
- We detected 2 emission line sources and no continuum source.
- One is likely to be a gas-rich SMG at z=3.335.
  - In this case, the velocity difference from the Lyα line center is +160 km/s, supporting the idea that the line is CO(4-3) at z=3.33554.
  - The molecular mass is as large as 3e11 Msun, comparable to a CO counterpart of z~2 DLA (Neeleman et al. 2018).
  - The physical distance from the DLA is 71.0 kpc, which is 2x further than the z~2 example.
  - The DLA is located on a straight line connecting the SMG and an LBG at the same redshift, suggesting that the DLA is a part of the cosmic web.
- The other is associated with a foreground galaxy of z(photo)=1.1.
  - The emission line is probably CO(2-1) at z=1.18.
  - The molecular mass is 4e10 Msun.