ALMA fellow program report: Far-infrared nebular emission lines and physics of interstellar medium of star-forming galaxies in the reionization epoch

Takuya Hashimoto (OSU, NAOJ)
on behalf of A. K. Inoue

Achievement in Cy 5 proposals

11 PI + CoI proposals submitted (7 proposals accepted)

Aims: investigating ISM properties at z > 6 with FIR lines

(1) 2017.1.00190.S PI: Akio K. Inoue Grade B
Physics of the interstellar medium of galaxies in the reionization era: the [OIII]-to-[CII] line ratio II

(2) 2017.1.00268.S PI: Akio K. Inoue Grade C
Nitrogen abundance in a z=7.2 Lyalpha emitter

(3) 2017.1.01305.S PI: Akio K. Inoue Grade C
[OIII]88, [CII]158 and dust continuum survey in a z=8.4 hyper overdensity of galaxies

(4) 2017.1.01195.S PI: Takuya Hashimoto Grade B
The first detection of the [OIII]88um from Two QSO host galaxies in the reionization epoch

(5) 2017.1.00225.S PI: Yoichi Tamura Grade A
FIR [O III] and [C II] emission from a z ~ 8 candidate galaxy: A glimpse into early production of heavy elements

(6) 2017.1.00508.S PI: Yuichi Harikane Grade A
Investigating ISM Physics at z~6 with Multiple FIR Lines of Newly-Discovered Luminous Galaxies

(7) 2017.1.00775.S PI: Darach Watson Grade B
Mapping all phases of the ISM in a normal reionisation-epoch galaxy

Achievement in journal papers

1 paper already submitted and 2 papers in preparation

(1) T. Hashimoto et al. (2018 a) submitted

(2) T. Hashimoto et al. (2018 b) in preparation

(3) Y. Tamura incl. AKI, TH et al. in preparation

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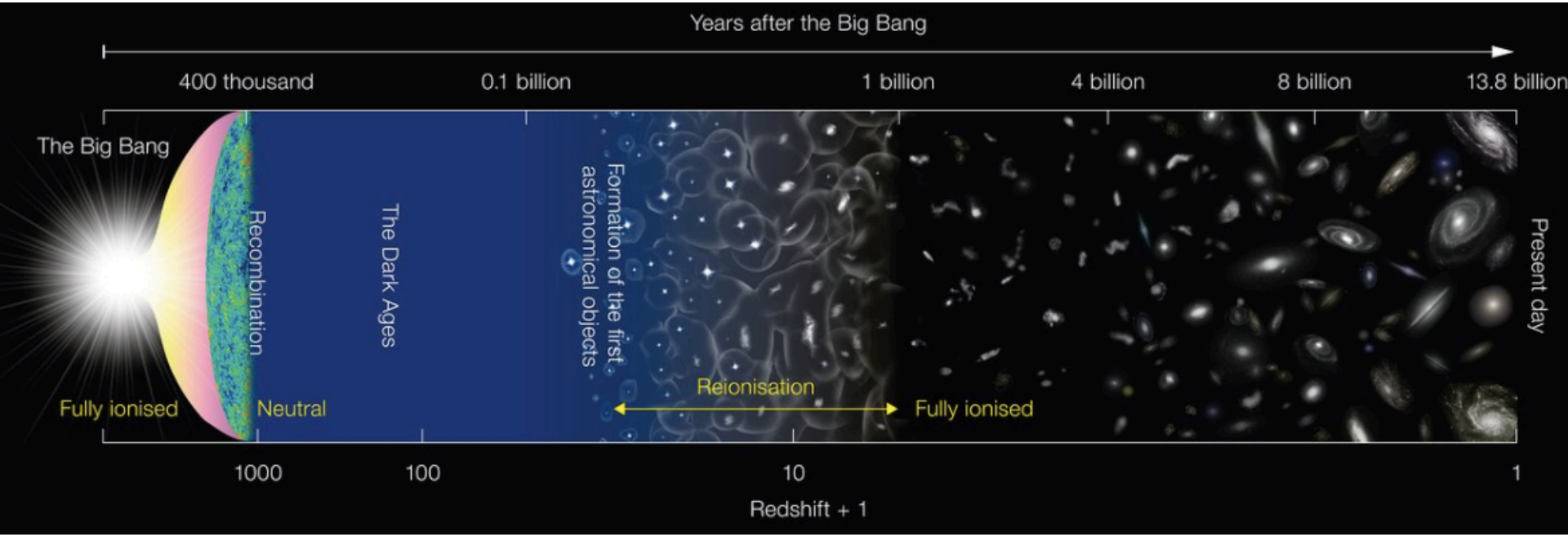
Simultaneous detections of Lyα, [OIII] 88, [CII] 158, and dust in a galaxy at z ~ 7.15 (Universe age ~ 750 Myr)

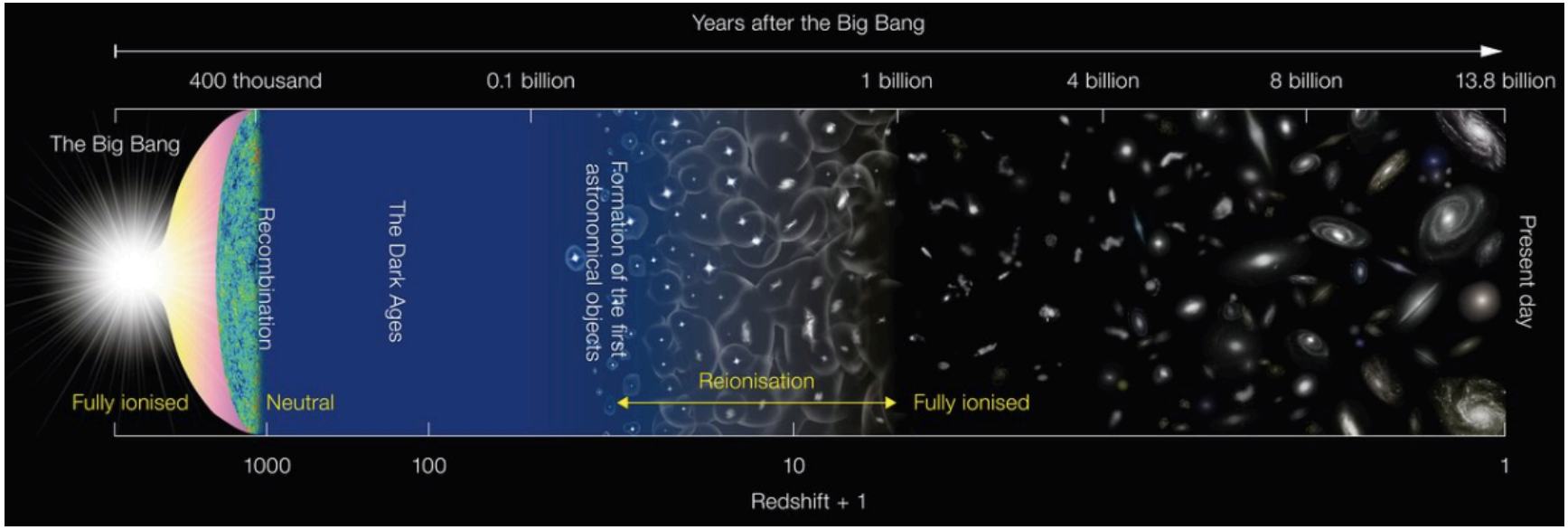
Takuya Hashimoto (OSU, NAOJ)

ALMA and reionization studies

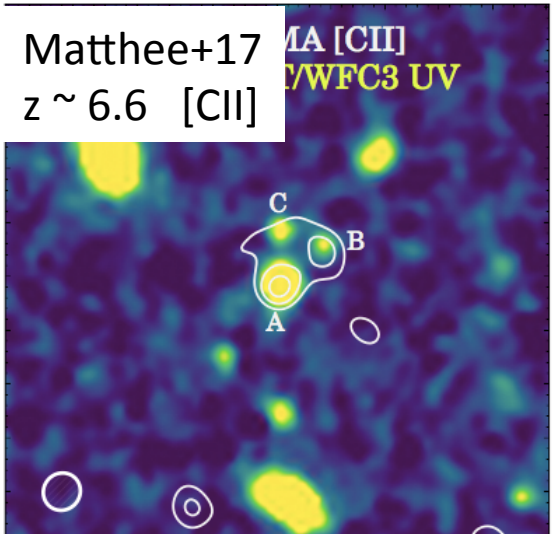


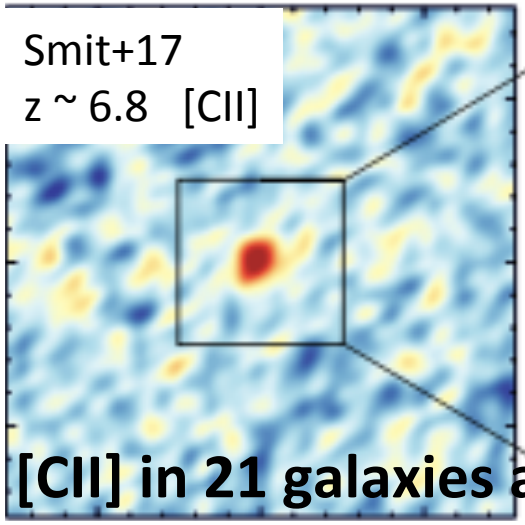
How reionization has completed ?

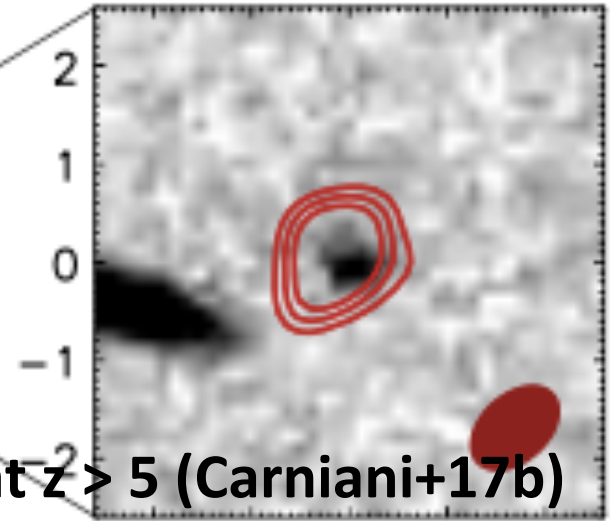
ALMA and reionization studies



- Rest-frame far-Infrared (FIR) emission lines (e.g., [CII] 158, [OIII] 88)
  - Spec-idenify galaxies in the EoR (z > 6 – 7)

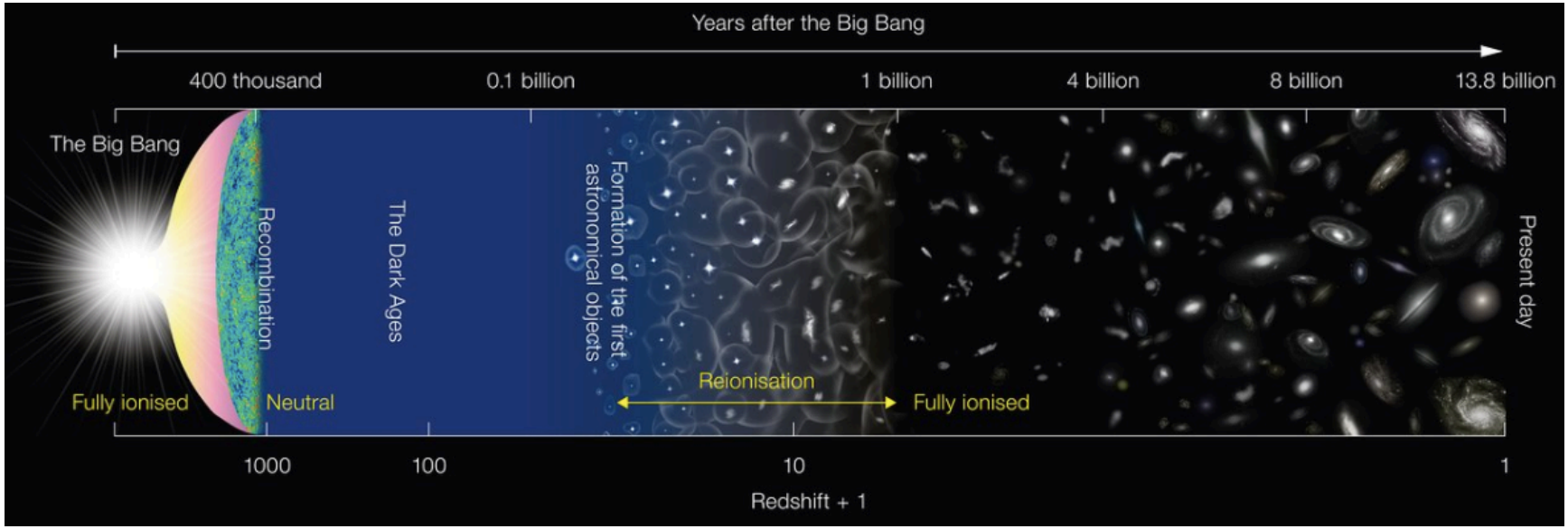






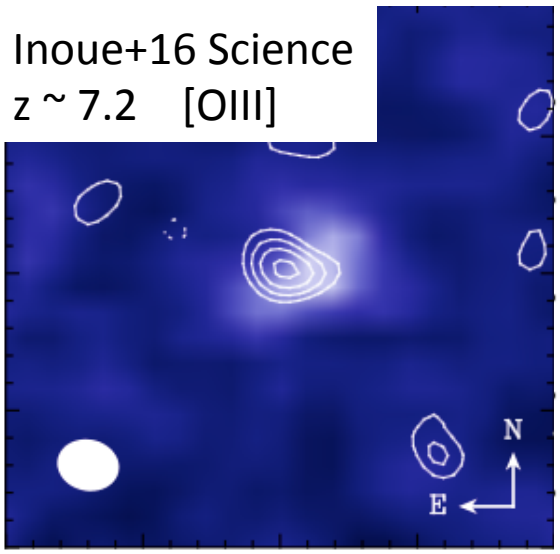
[CII] in 21 galaxies at z > 5 (Carniani+17b)

ALMA and reionization studies

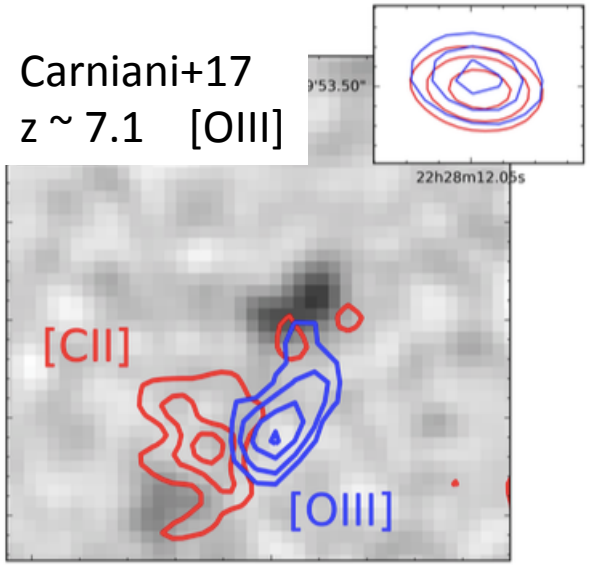


- Rest-frame far-Infrared (FIR) emission lines (e.g., [CII] 158, [OIII] 88)
  - Spec-identify galaxies in the EoR (z > 6 – 7)

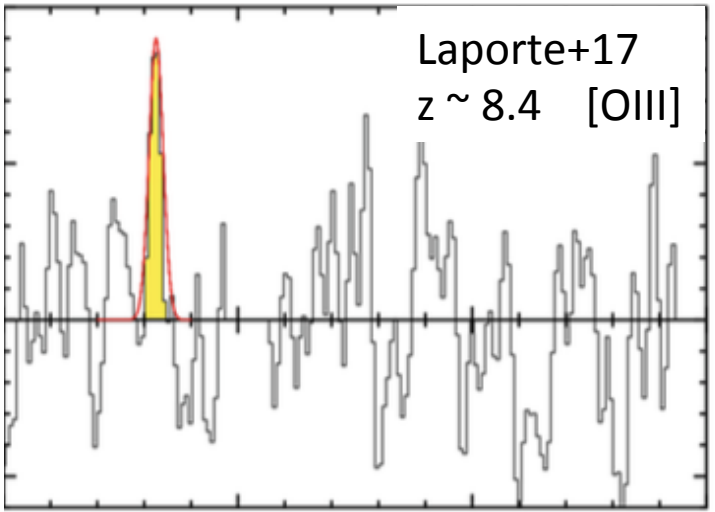
Inoue+16 Science
z ~ 7.2 [OIII]



Carniani+17
z ~ 7.1 [OIII]



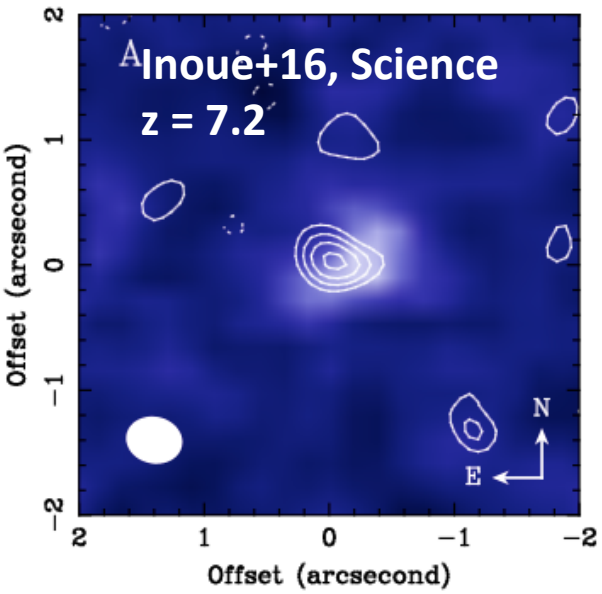
Laporte+17
z ~ 8.4 [OIII]

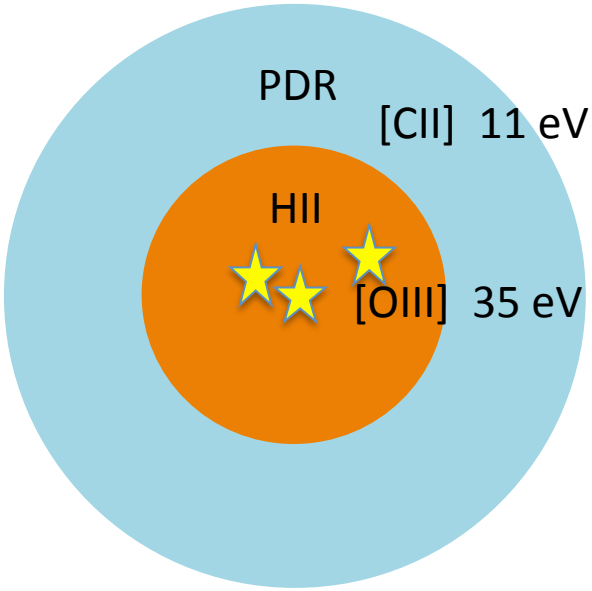


ALMA and reionization studies

- [OIII]/[CII] as a diagnostic tool of ISM (Inoue+16)

SXDF-NB1006-2





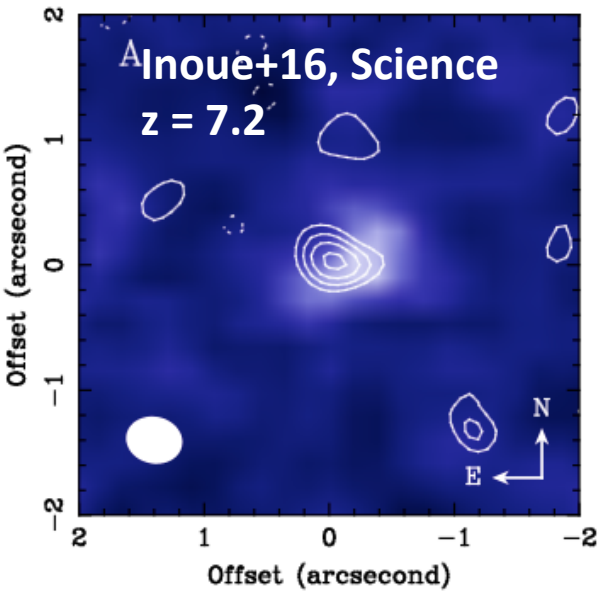
Very high [OIII]/[CII] ratios > 12 (3σ); the highest in external galaxiex

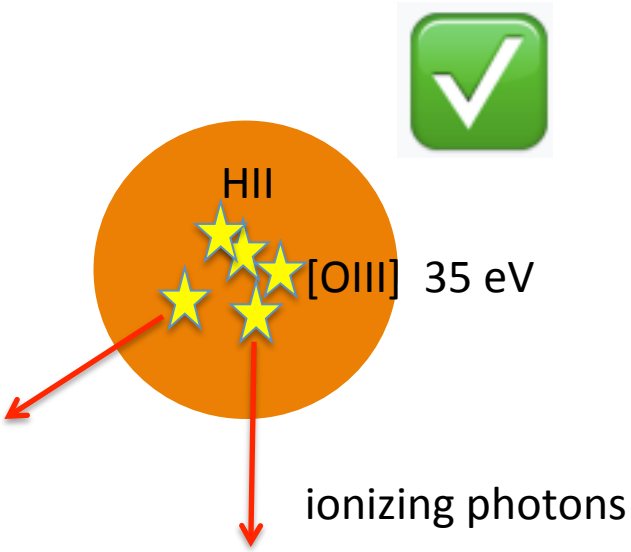
Unusually low neutral gas in the ISM → High LyC escape ?

ALMA and reionization studies

- [OIII]/[CII] as a diagnostic tool of ISM (Inoue+16)

SXDF-NB1006-2





Very high [OIII]/[CII] ratios > 12 (3σ); the highest in external galaxies

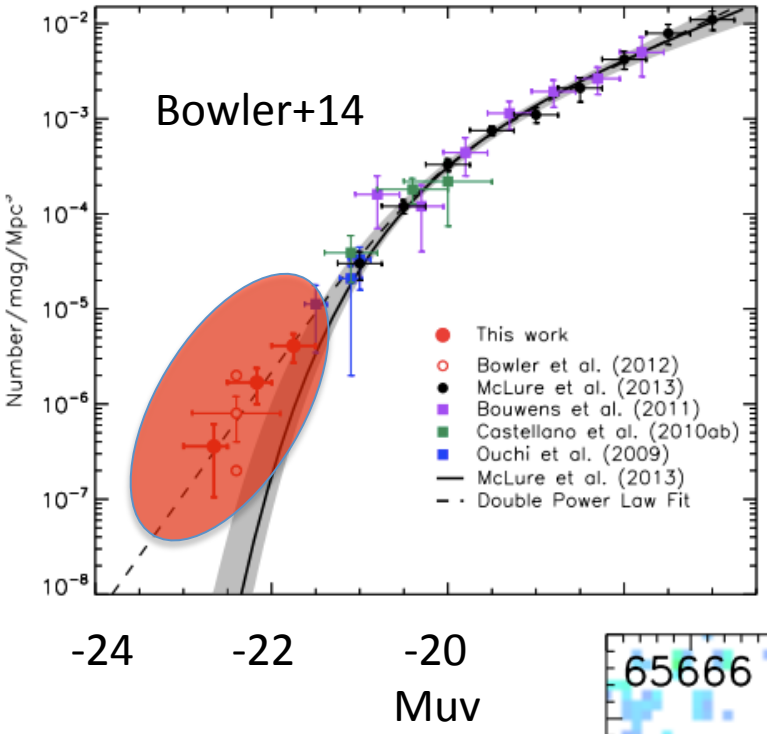
Unusually low neutral gas in the ISM → High LyC escape ?

A larger sample is needed for a definitive conclusion

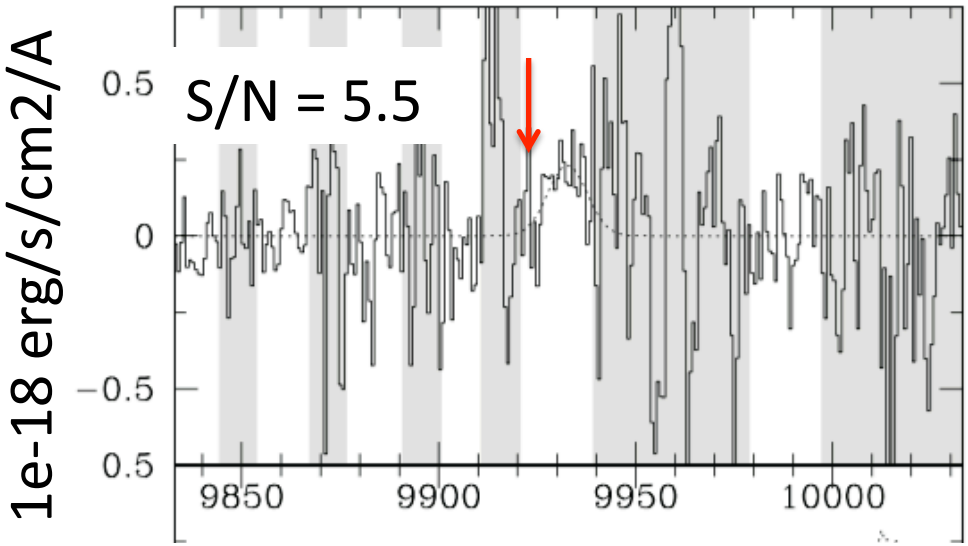
→ This study (and Cy 5 proposals)

B14-65666: a very UV bright dropout galaxy

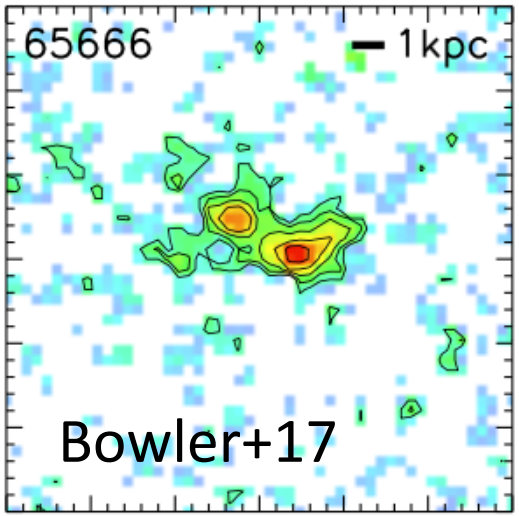
UV luminosity function “bump”



Lyα identified in Furusawa+16



Obs wavelength (Ang)



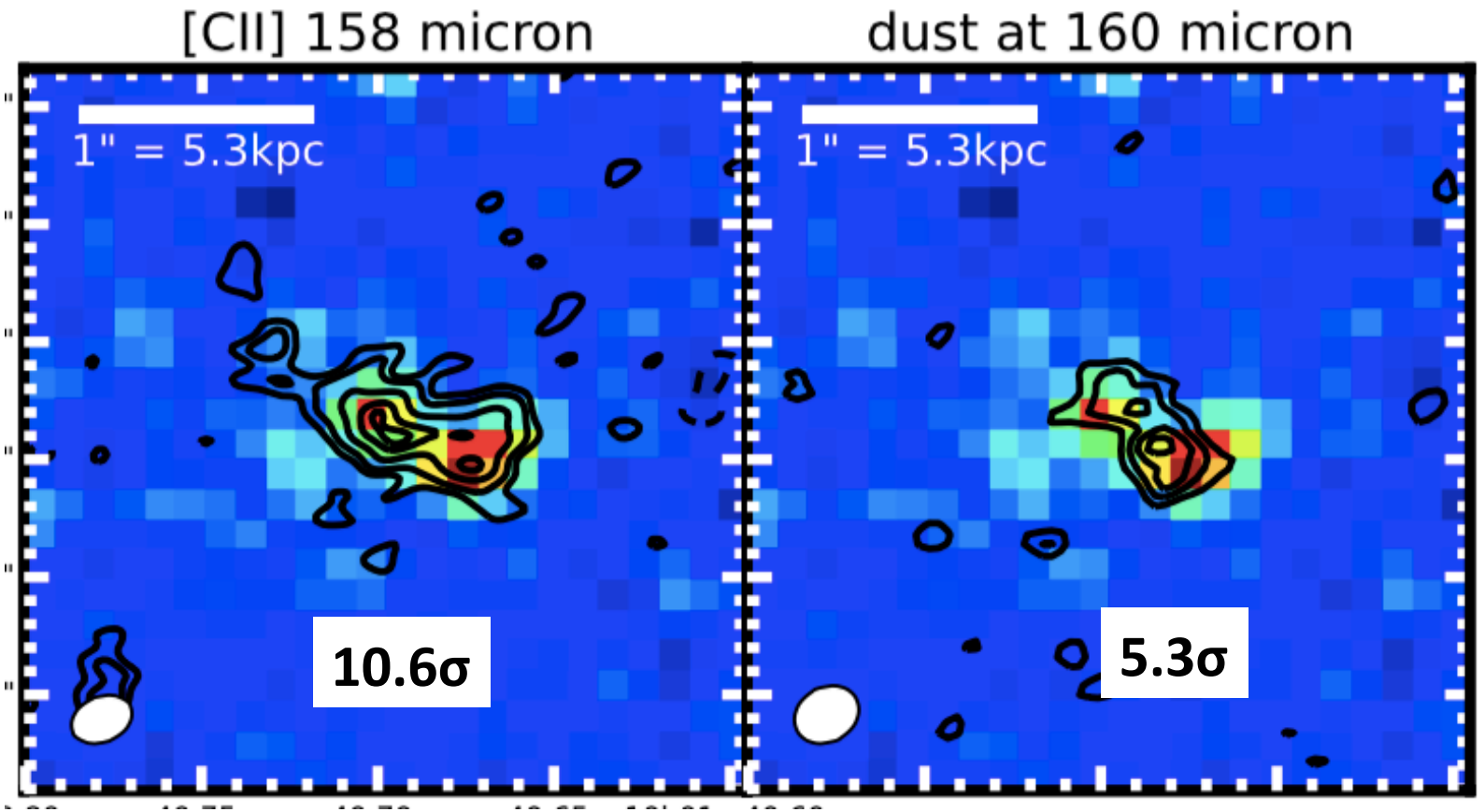
F140W (rest-frame UV)
two-components

Cy 4 ALMA Band 6 & 8 Observations (PI: A. K. Inoue)

Band	# of anntena	Ton [min]	beam size [FWHM]	1σ continuum
Band 6 [CII] 158	40	~120	0”.27 x 0”.19	10 μJy/B
Band 8 [OIII] 88	40	~50	0”.31 x 0”.27	62 μJy/B

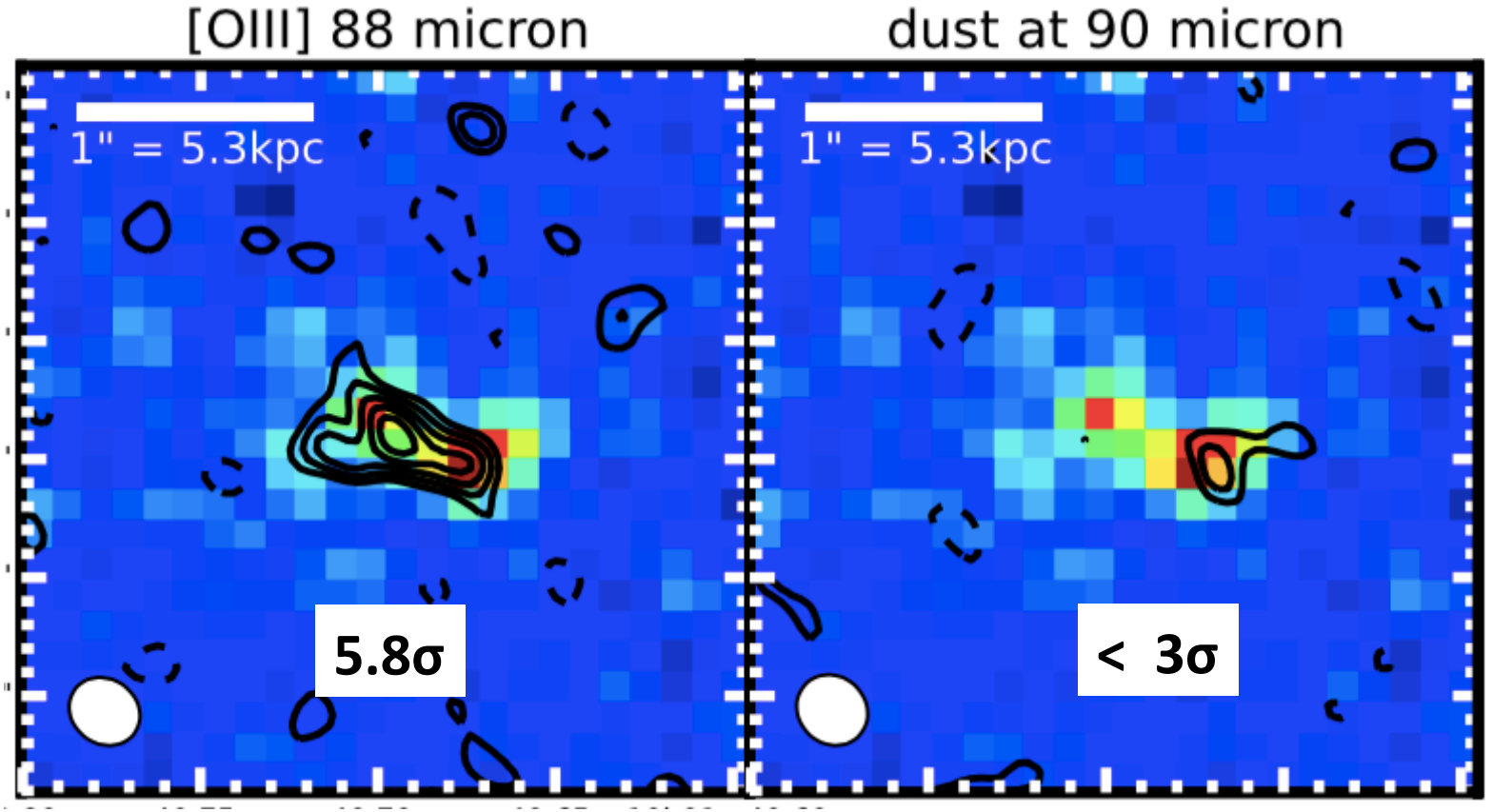
- CASA 4.7.0
- natural weighting

Band6: [CII] 158 µm and dust emission



- integrated [CII] flux = 1.0 ± 0.1 Jy km/s
- L([CII]) = (1.3 ± 0.13) x 10^9 Lsun
- $S_{160\mu m}$ = 130 ± 25 µJy

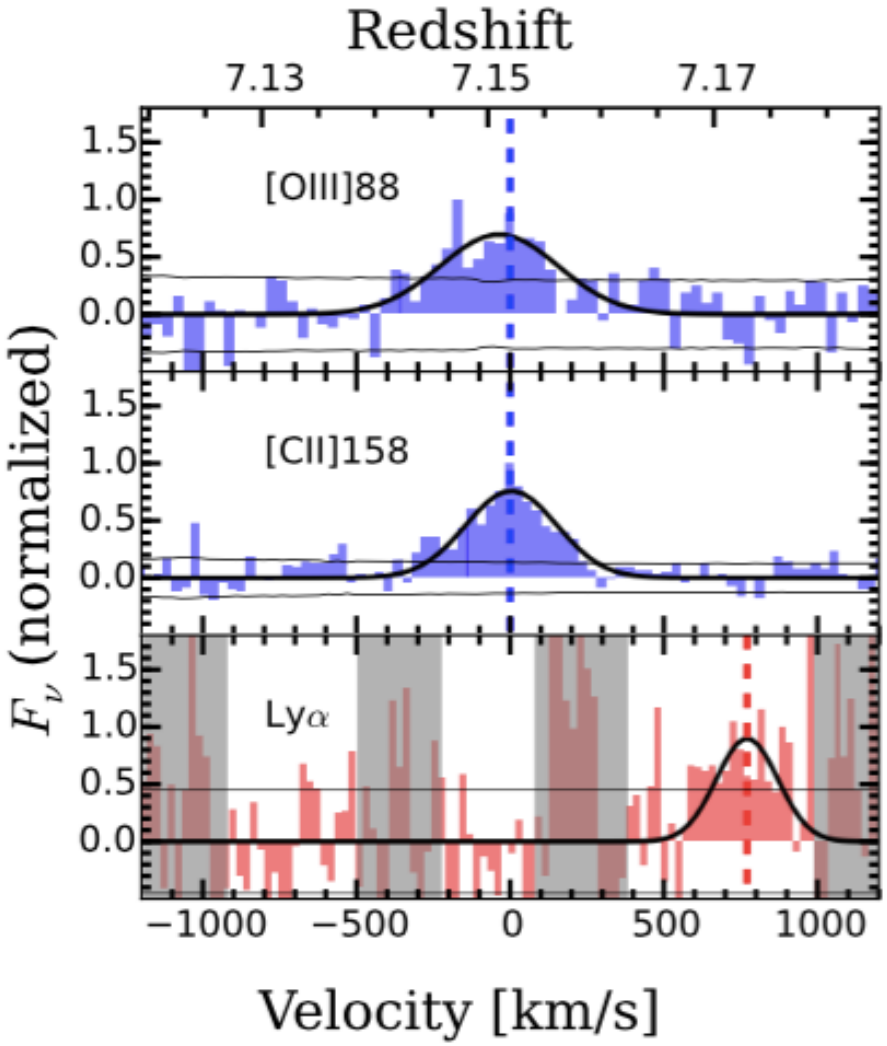
Band8: [OIII] 88 μm



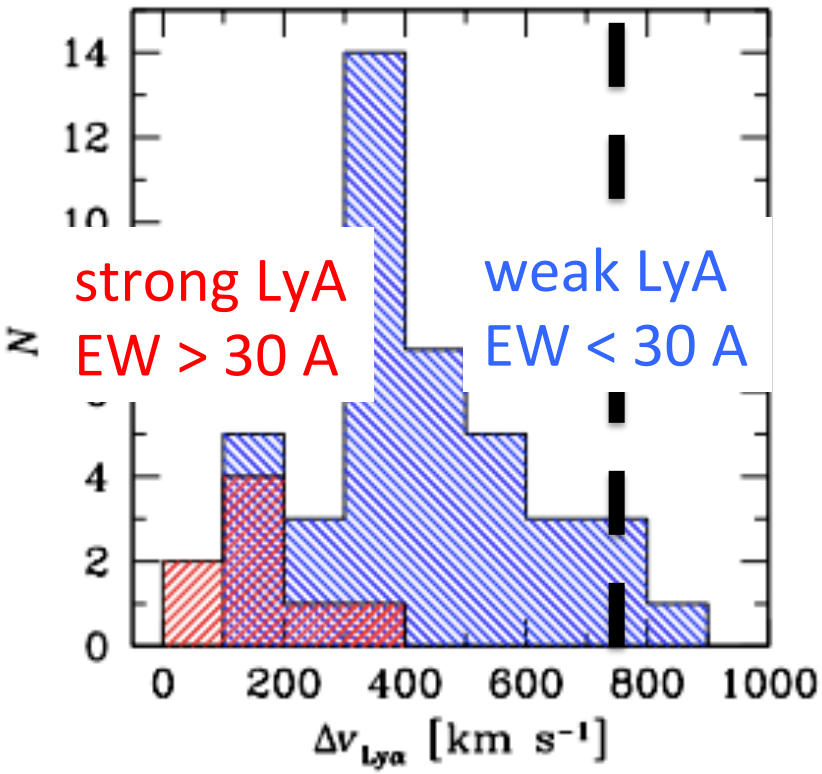
- integrated [OIII] flux = 1.3 ± 0.2 Jy km/s
- L([OIII]) = (2.9 ± 0.5) x 10^9 Lsun

-[OIII]/[CII] ~ 2 cf., [OIII]/[CII] > 12 (3σ) ; Inoue+16

A very large Lyα velocity offset



z～2–3 galaxies (Hashimoto+13)

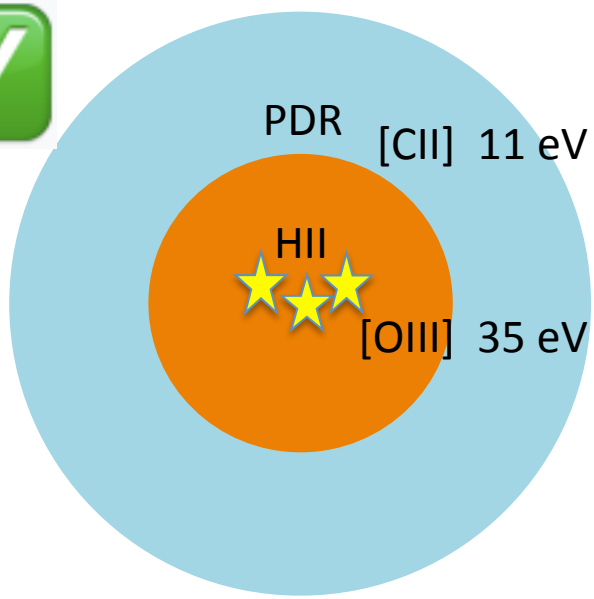


*very roughly Δv express NHI
(Verhamme+06, Dijkstra+06)

Δv = 770 ± 50 km/s, EW=4 Å

cf., Δv = 110 ± 30 km/s, EW=33 Å (SXDF-NB1006-2; Inoue+16)

Large Δv(Lyα) + low [OIII]/[CII] ➔ low f_{esc}



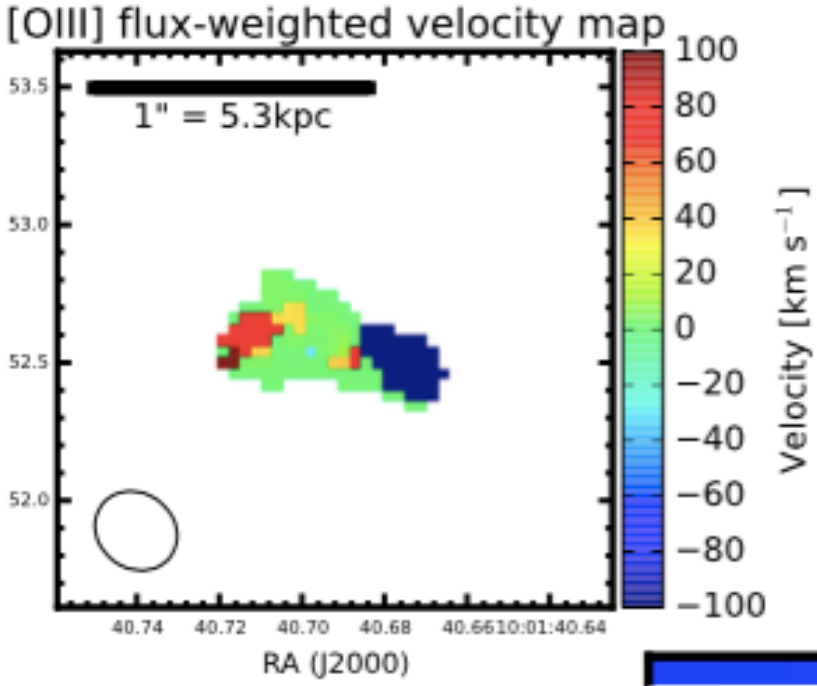
B14-65666 (This study)

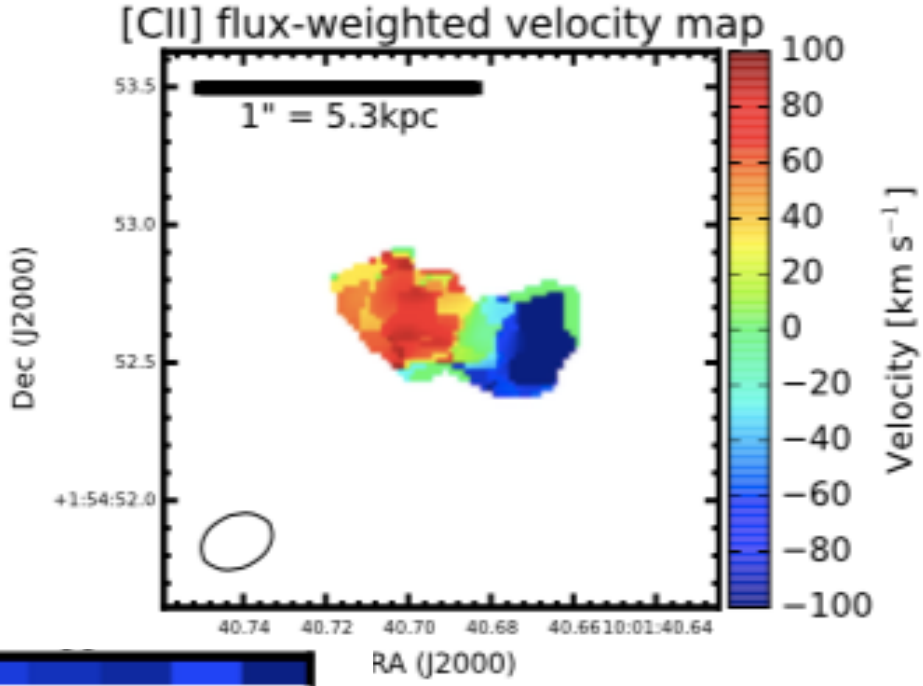
SXDF-NB1006-2 (Inoue+16)

Both the large Δv(Lyα) and low [OIII]/[CII] ratio suggest that B14-65666 has a large amount of neutral gas (unlike SXDF-NB1006-2)

-- log N_{HI} ~ 21-22 (e.g., Verhamme+06, 08) → fesc ~ 0 %
but the picket-fence scenario possible

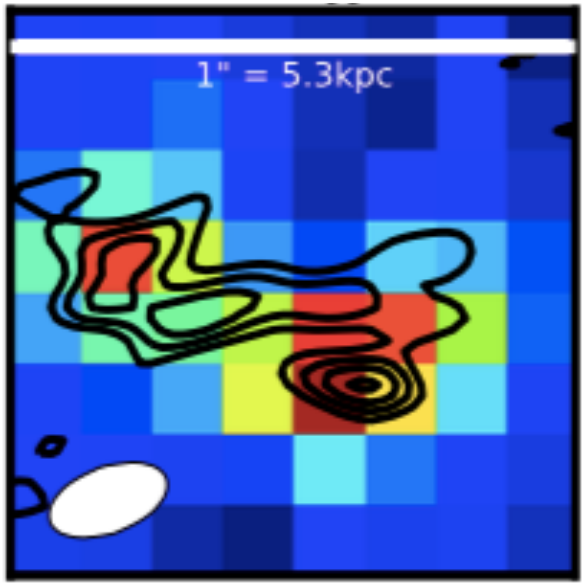
The most distant velocity gradient: merger ?





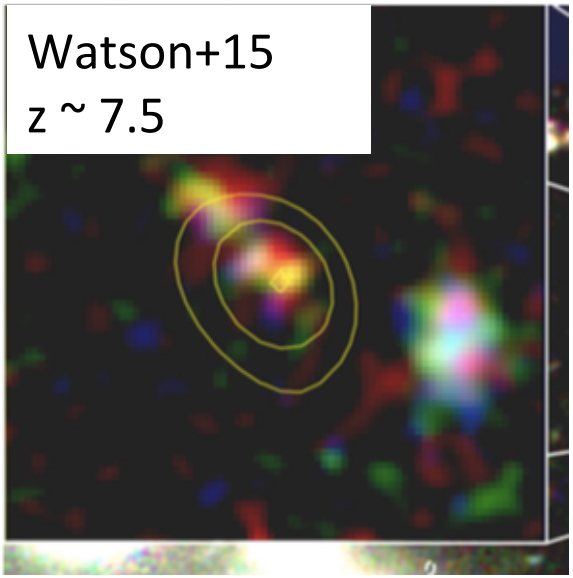
~ 200 km/s gradient

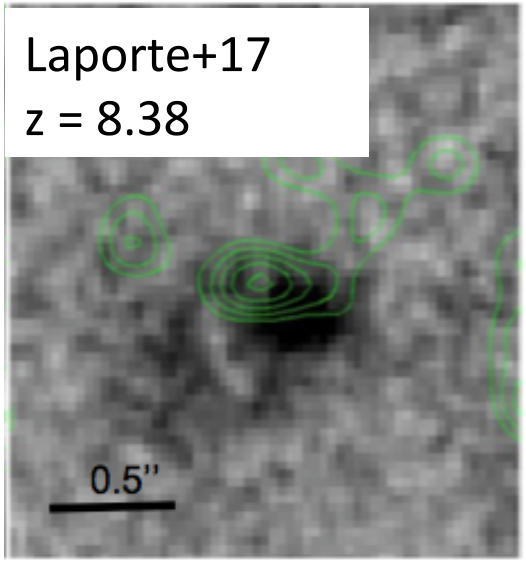
Data points > 3σ pixels

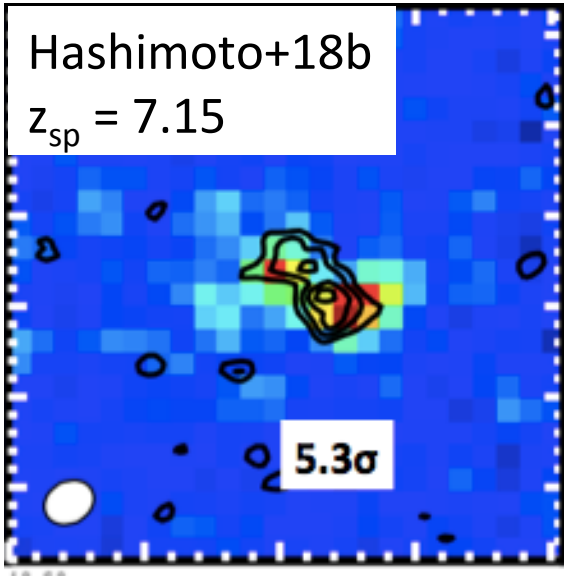


Re-analyzed [CII] mom0 with Briggs weighting robust = 0.3

Dust in the EoR







- The fourth galaxy with dust continuum at z > 7 (Tamura-san's poster)

- L_{TIR} = [1.6 – 5.7] x 10^{11} Lsun
(modified black-body; T_d = 30 – 50 K, β_d = 1.5; Ouchi+13, Knudsen+17)

- M_d = [1.1 – 5.2] x 10^7 Msun, M_d/M_* ~ 0.01

$$\kappa = \kappa_0 (\mu/\nu_0)^{\beta_d}$$
$$\kappa_0 = 10\ \mathrm{cm^2\ g^{-1}}\ \text{at}\ 250\ \mu\mathrm{m}$$

→ implications on dust formation and growth mechanisms (future)

Summary

- 7/11 PI and CoI proposals accepted for Cy 5

- 1 paper submitted and 2 papers in prep.
  -Hashimoto+18a, b in prep. , Y. Tamura+18 in prep.

- The first complete set of Lyα, [OIII] 88, [CII] 158, and dust
  - [OIII]/[CII] ~ 2
  - Δv(Lyα) ~ 770 km/s
  - Velocity gradient in [OIII] and [CII] + HST image (merger/rotation)
  - L_{TIR} = [1.6 – 5.7] x 10^{11} L_o and a dust mass fraction ~ 0.01
  - future constraints on the dust garin growth mechanisms

- [OIII]/[CII] ratio in other high-z populations
  - SMGs: Marrone+17 at z = 7.0 (0.5 – 2.0)
  - QSOs: T. Hashimoto+ (Cy 5) z = 6 (? ? ?)