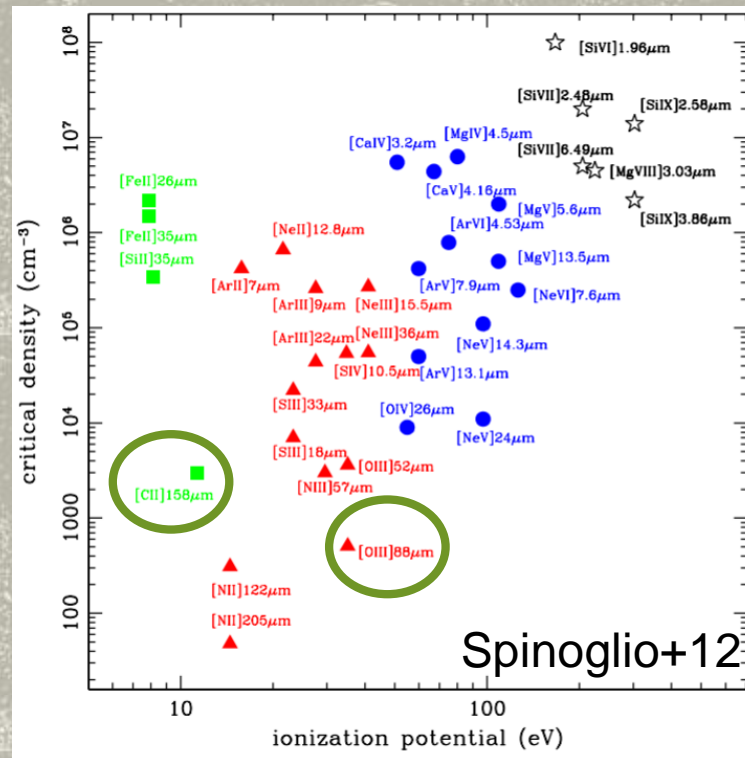


SCIENCE REVIEW OF HIGH-Z GALAXY

Akio K. Inoue (Osaka Sangyo U.)

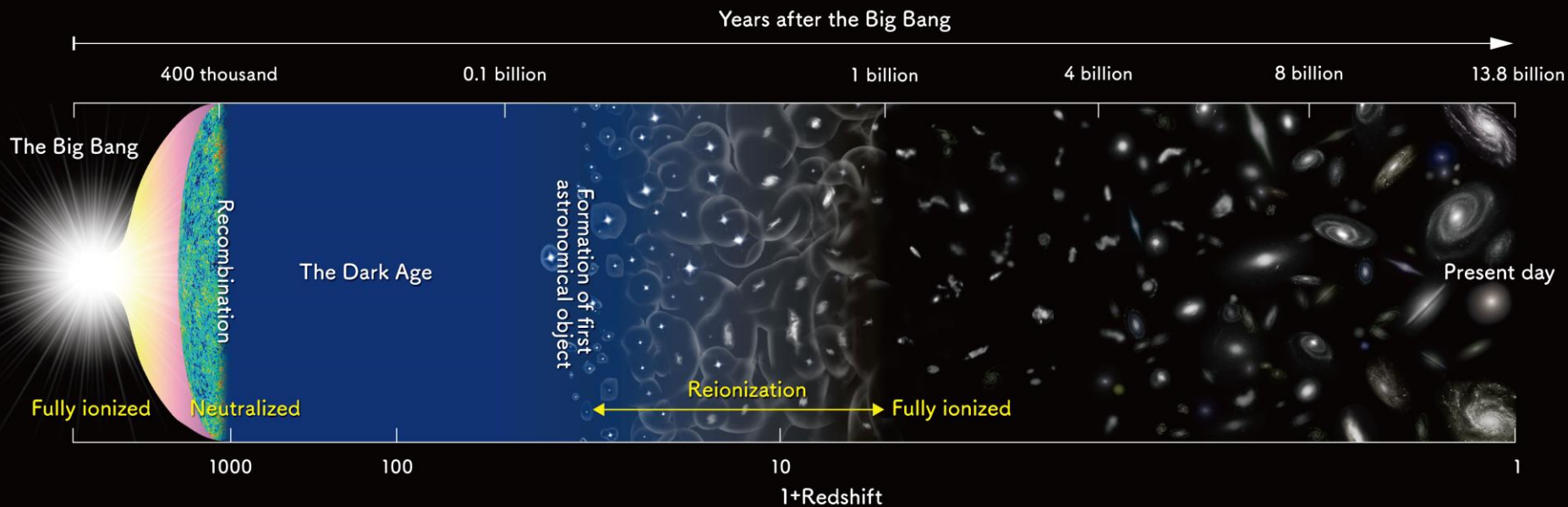
SCOPE OF THIS TALK

- An review of 2016 ALMA results about galaxies at $z > 6$: **Epoch of Cosmic Reionization**
- Especially, emission lines of [CII]158 and [OIII]88.



EPOCH OF COSMIC REIONIZATION

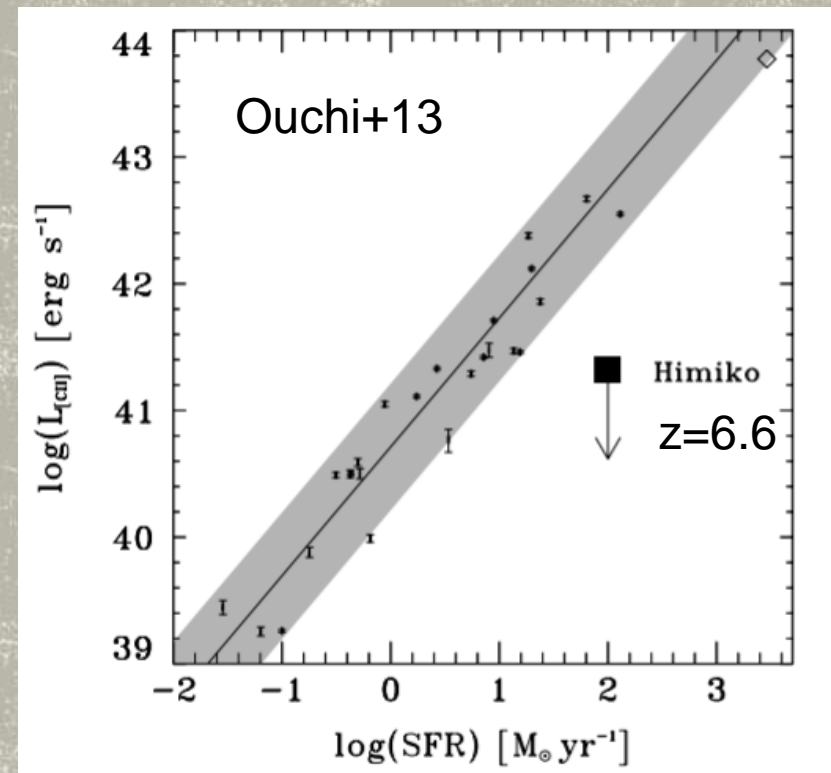
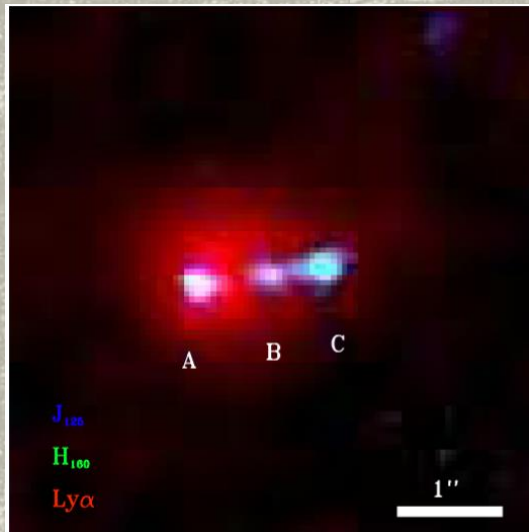
- First billion years in the cosmic history
 - Redshift $z \sim 6$ — 20
- Epoch of the first objects and galaxies
 - The first metal and dust



[C II] 158 μm LINE IN THE EOR

- The [CII] line is one of the strongest emission lines in the local Universe.
 - $L_{\text{[CII]}}/L_{\text{TIR}} \sim 1\%$
- However,...

very weak in the EoR?



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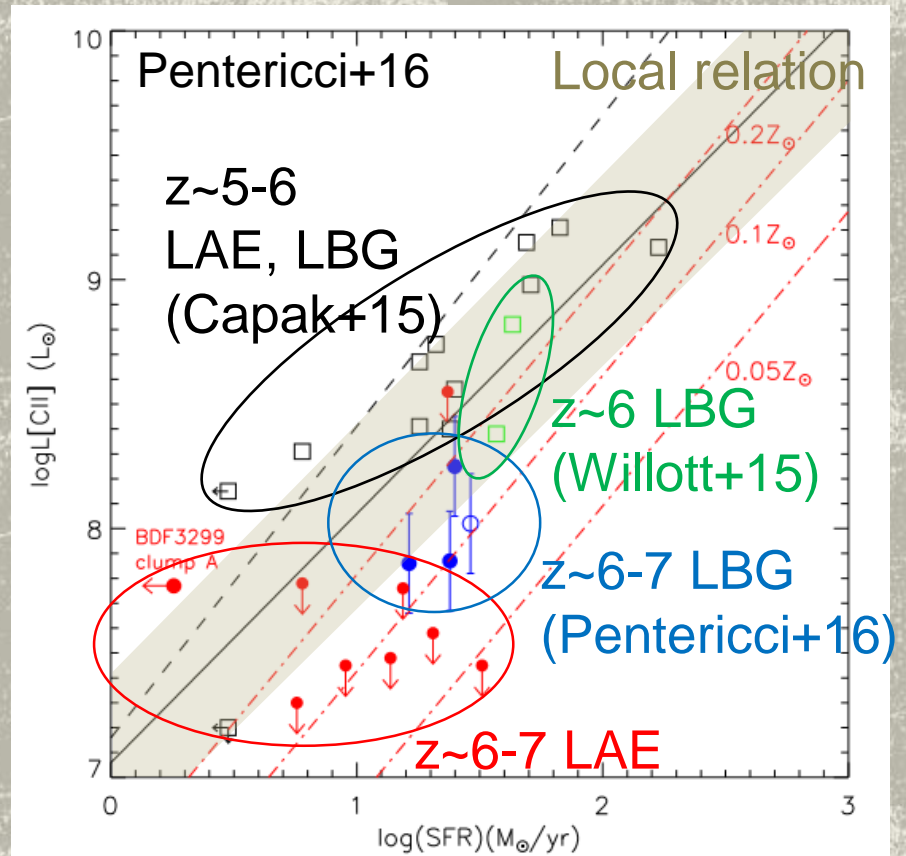
very weak in LAEs

in the EoR!

- $\text{Ly}\alpha$ and [CII] anti-correlation?
(Harikane+ ASJ16b)

LBG: Lyman break galaxy
(UV continuum selection)

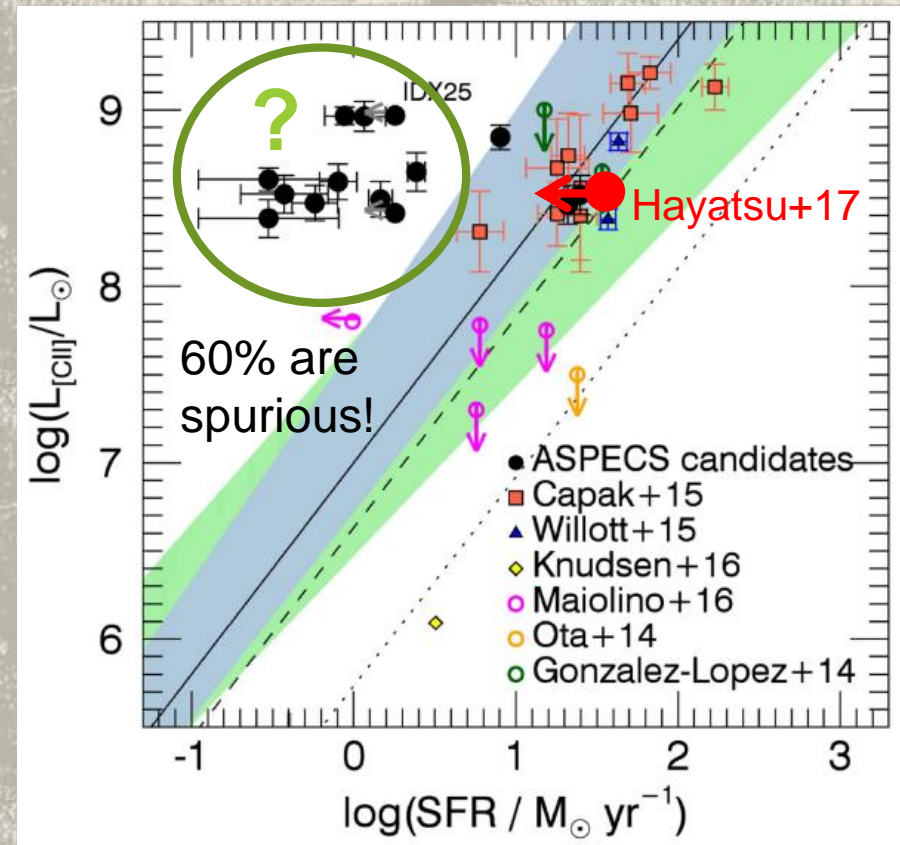
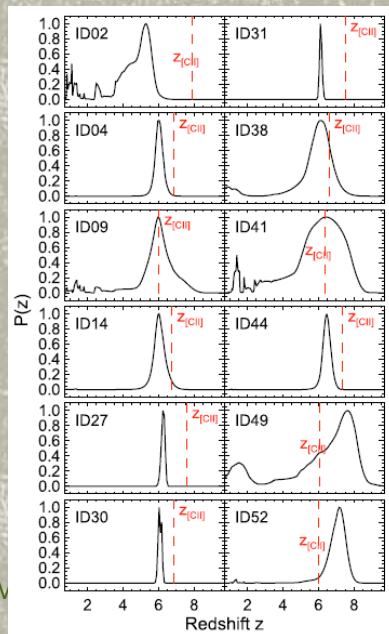
LAE: $\text{Ly}\alpha$ emitter
($\text{Ly}\alpha$ emission line selection)



[C II] 158 μm LINE IN THE EOR

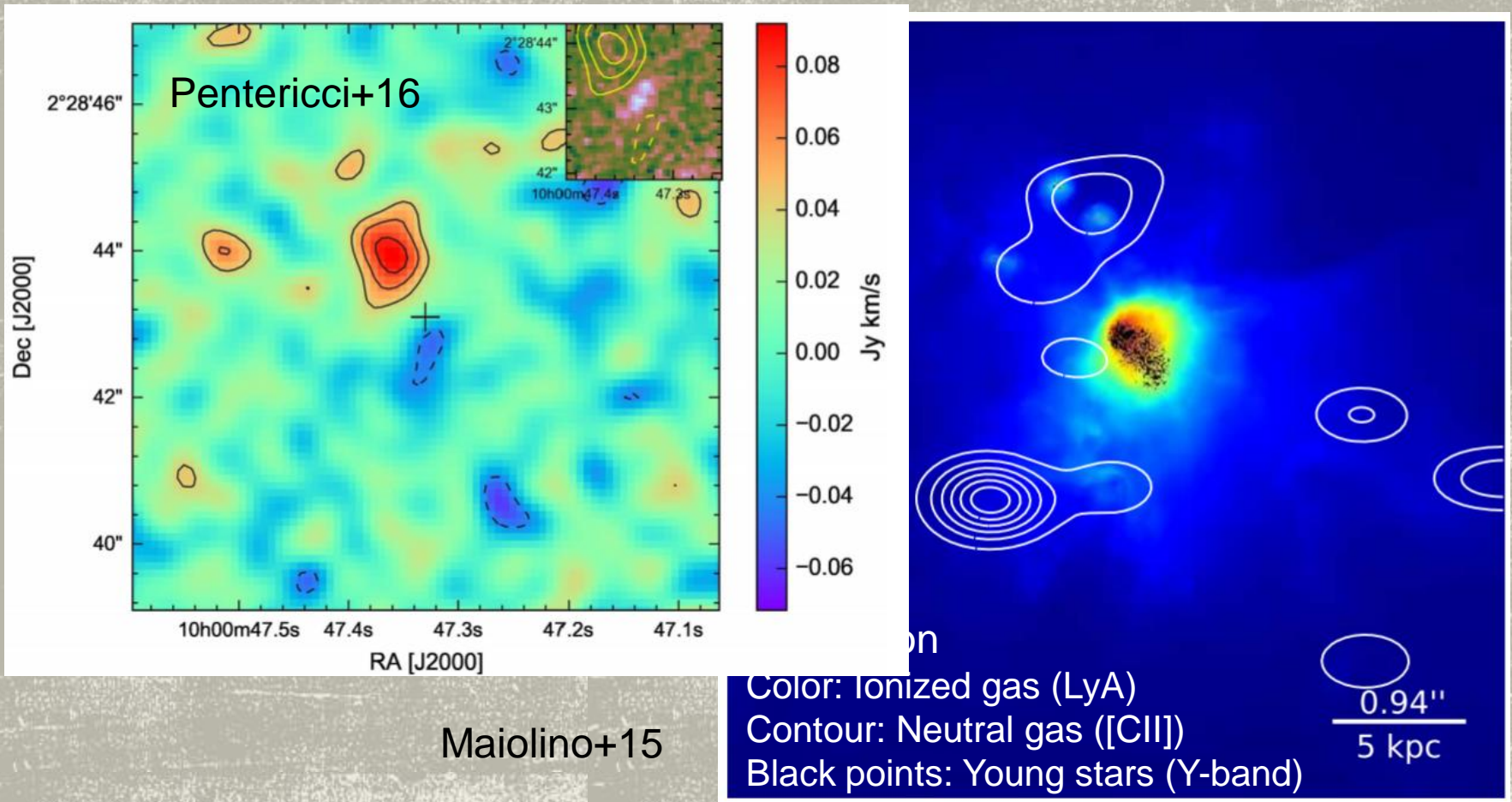
- The [CII] line is one of the strongest emission lines in the local Universe.
 - $L_{\text{[CII]}}/L_{\text{TIR}} \sim 1\%$
- However, ... some LBGs are **over-luminous in [CII]??**

Photo-zs are not very consistent with [CII] lines.



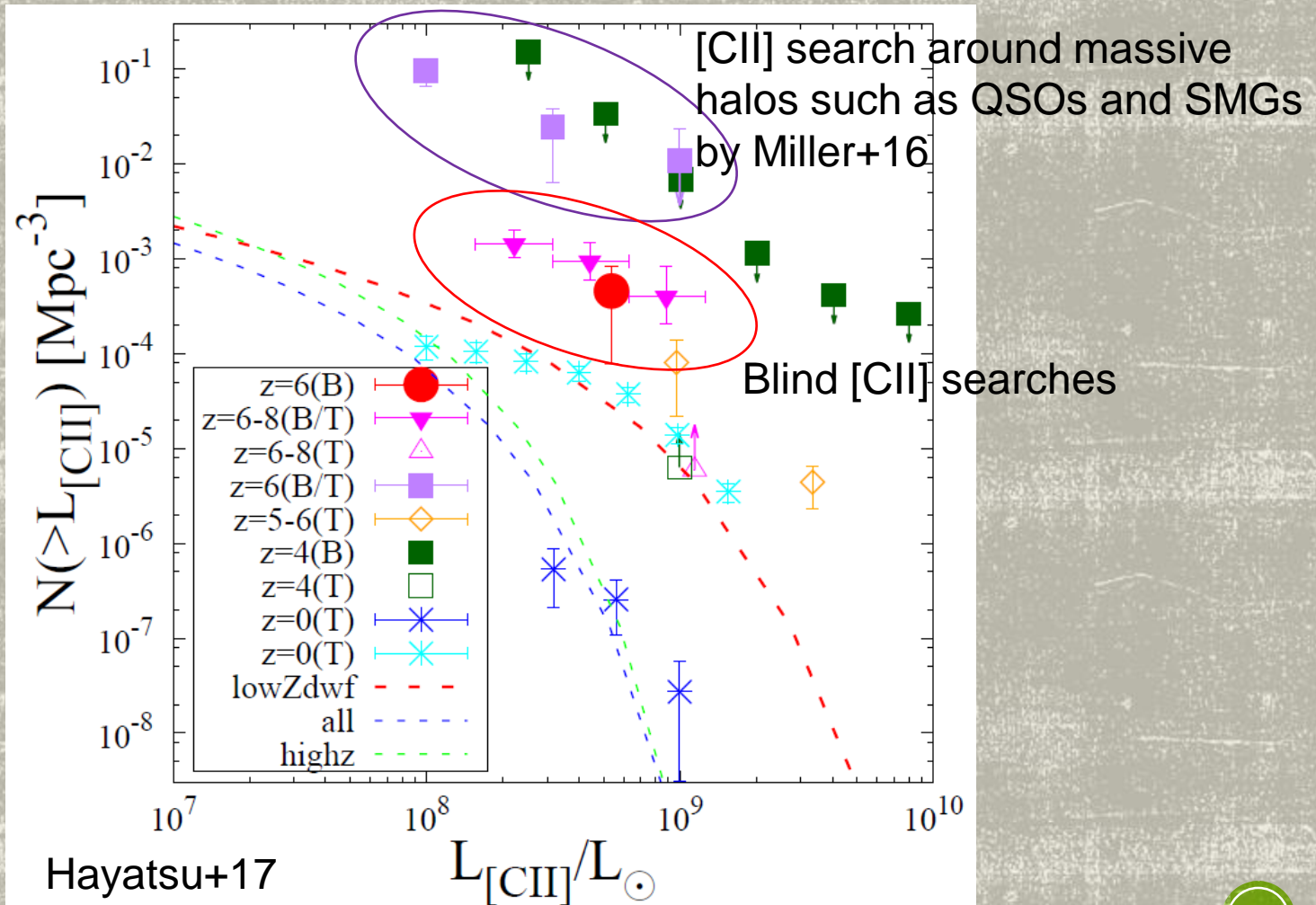
[C II] 158 μm LINE IN THE EOR

- Spatially offset [CII] line?



[C II] 158 μm LINE IN THE EOR

- The [CII] line luminosity functions.

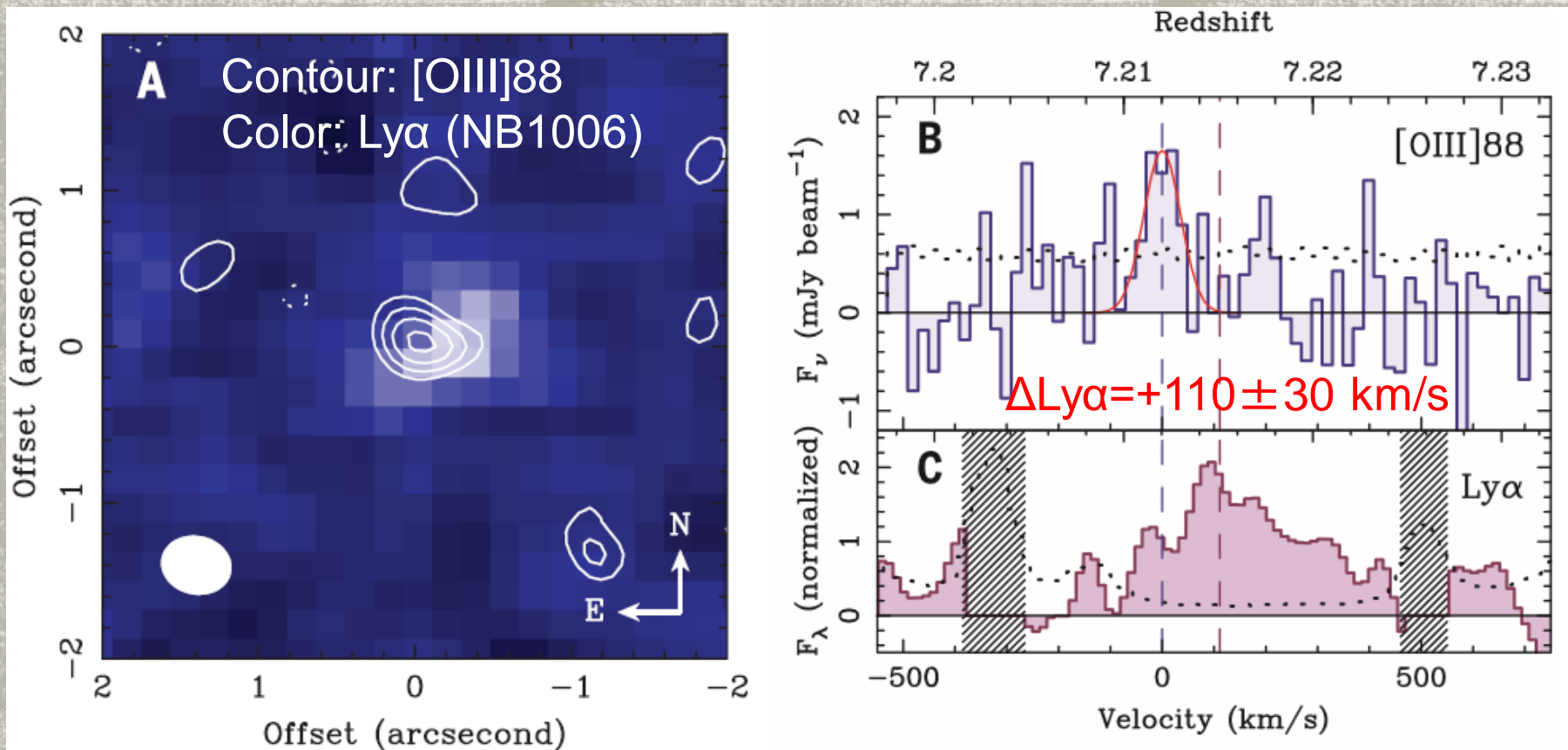


[C II] 158 μm LINE IN THE EOR

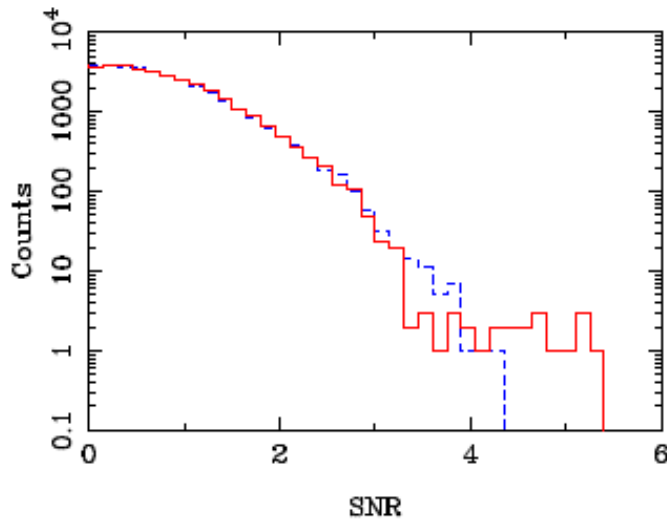
Object	Redshift	EW(LyA) [Å]	L[CII]/SFR [$1e7L_{\odot}/\text{Mo yr}^{-1}$]	Reference
1 A1689-zD1	7.6031 ?	3 σ	0.14 ? (SFR=13)	Knudsen+16b
2 ID27	7.575 ?	-	8 (SFR=10.5)	Aravena+16
3 z8-GND-5296	7.508	8	<0.03 (SFR=330)	Schaerer+15
4 ID31	7.494 ?	4.5 σ 0.7"off	2.7 (SFR=12.4)	Aravena+16
5 IDX34	7.491 ?	5.3 σ Blind	-	Aravena+16
6 SXDF-NB1006-2	7.2120	33	<0.02 (SFR=350)	Inoue+16
7 COSMOS13679	7.1416	15	0.30 (SFR=24)	Pentericci+16
8 BDF-3299	7.109	50	<0.37 (SFR=6)	Maiolino+15
9 BDF-512	7.008	64	<1.00 (SFR=6)	Maiolino+15
10 IOK-1	6.96	24	<0.14 (SFR=24)	Ota+15

[O III] 88 μm LINE IN THE EOR

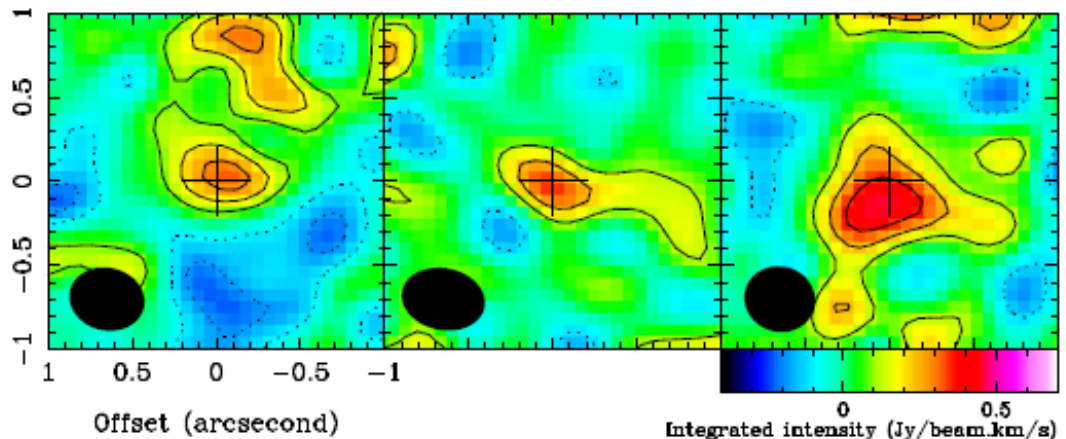
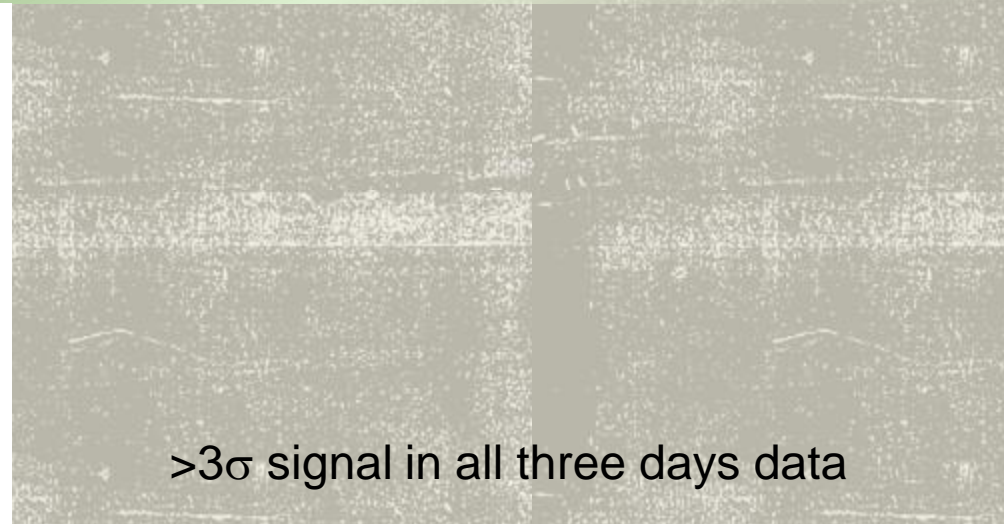
- First detection of [OIII] 88 μm in EoR (5.3σ).
 - $z([\text{OIII}])=7.2120 \rightarrow$ The most distant oxygen ever found!

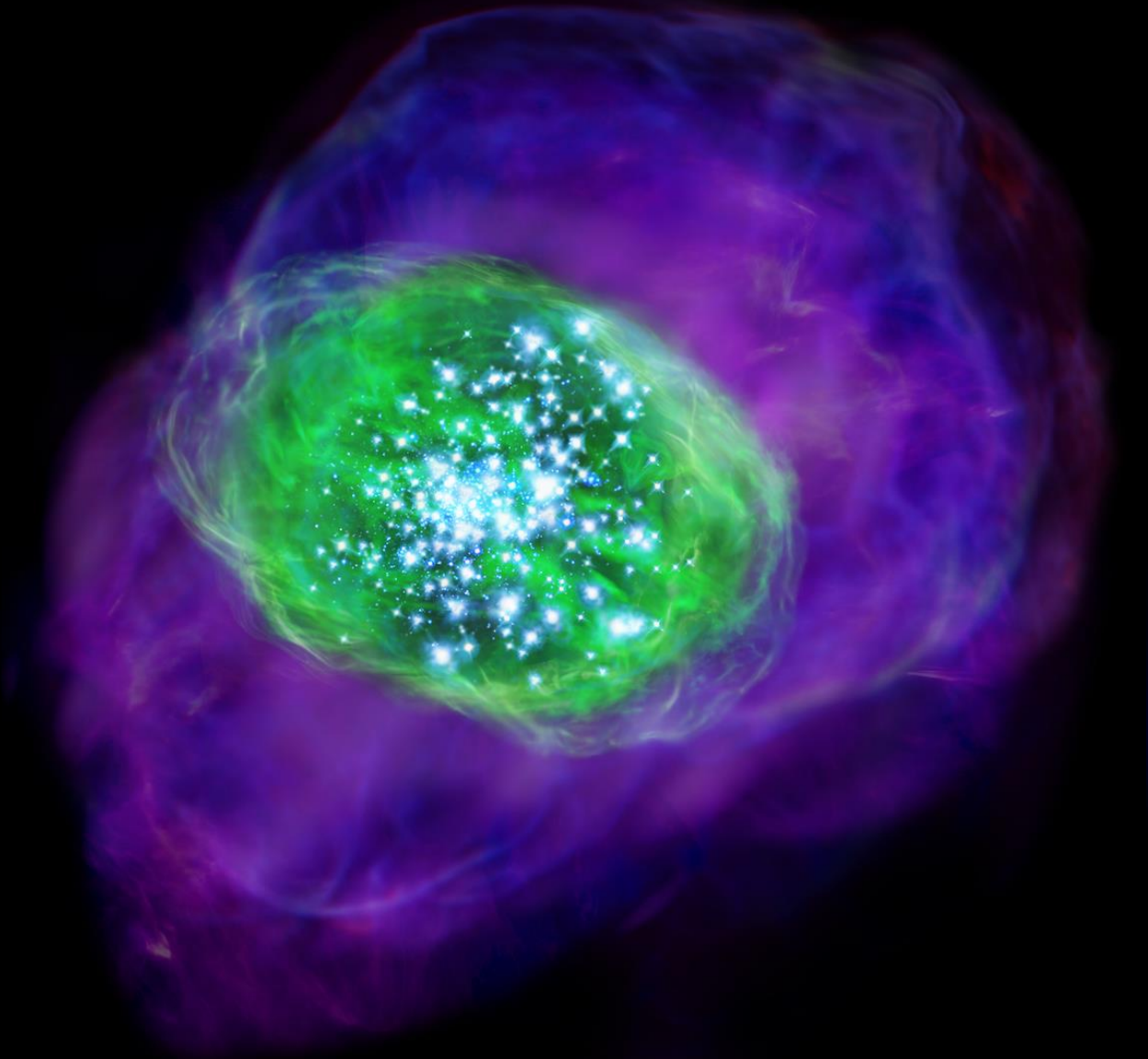


[O III] 88 μm LINE IN THE EOR



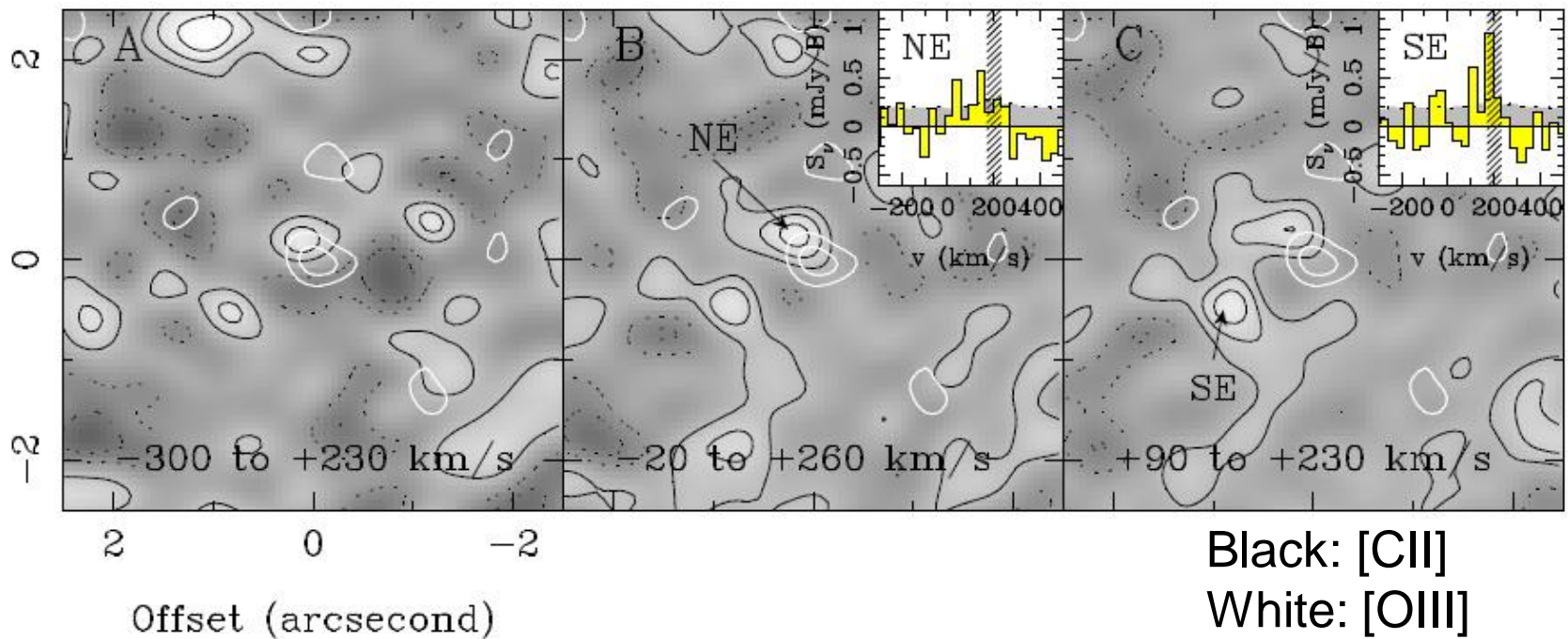
Pixel S/N distribution
Red: Positive
Blue: Negative





[O III] 88 μm LINE IN THE EOR

- Neither [CII] line nor dust continuum at the position of [OIII].

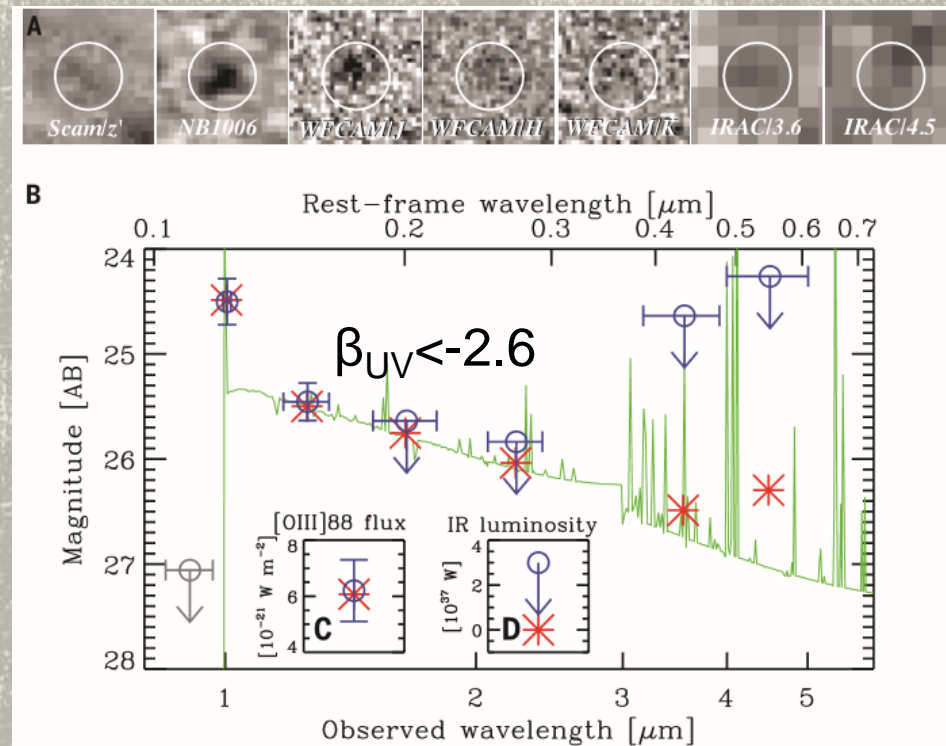


Inoue+16, Science

SED FITTING

[O/H]	$-1.0^{+1.0}_{-0.3}$
$\log(\text{SFR}[M_{\text{sun}}/\text{yr}])$	$2.54^{+0.17}_{-0.71}$
$\log(\text{age}[\text{yr}])$	$6.00^{+1.00}$
$\log(\text{Mstar}[M_{\text{sun}}])$	$8.54^{+0.79}_{-0.22}$
$E(B-V)$ [mag]	$0.00^{+0.04}$
f_{esc}	$0.54^{+0.17}_{-0.54}$
$\log(f_{\text{esc}} \xi_{\text{ion}}[\text{Hz/erg}])$	$25.44^{+0.46}_{-0.84}$

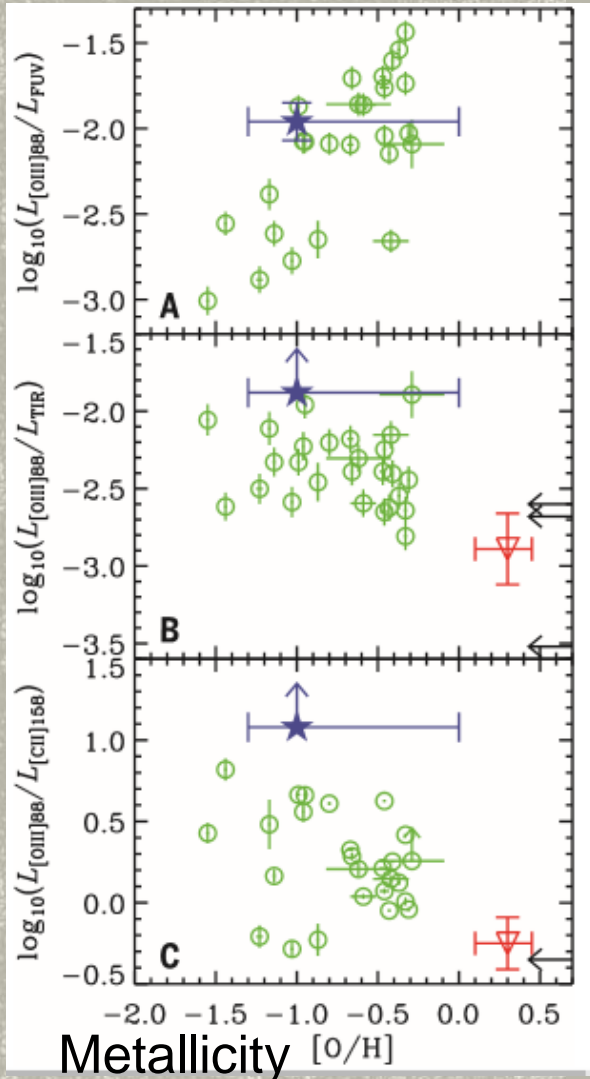
PEGASE2, Sapleter IMF, constant SFR, Calzetti dust law, nebular lines and continuum



Inoue+16, Science

[O III] 88 μm LINE IN THE EOR

[OIII]/CII [OIII]/IR [OIII]/UV



- SED fit \rightarrow [O/H] \sim -1
 - [OIII] line flux constrains [O/H] well.
- [OIII]/UV \sim Nearby dwarfs
- Large [OIII]/IR
 - Less dust
- Large [OIII]/[CII]
 - Weak [CII]
 - Less HI gas (PDR)

Inoue+16, Science

SUMMARY

- [CII] 158 line seems to be weak in LAEs at $z > 6$.
 - Anti-correlation between [CII] and LyA lines?
- Blind [CII] searches may have found $z \sim 6$ [CII] emitters without any counterpart.
 - [CII] over-luminous galaxies?
 - Spatial offset of [CII]?
- [OIII] 88 line was detected from an LAE at $z = 7.2$.
 - High [OIII]-to-[CII] line ratio \rightarrow Lack of HI gas
 - Opened a new window for probing the ISM in the EoR.

ALMA HzFINEST

High-z Far-Infrared Nebular Emission Study

- SXDF-NB1006-2 [OIII]88 line kinematics
 - Cycle3 DDT program
- SXDF-NB1006-2 [NII]122 line observations
 - Cycle4 Rank B
- [OIII]/[CII] ratio measurements
 - Cycle4 Rank B: 4 objects at $z=6--8$
- Higher- z [OIII]88 line observations
 - Cycle3 Rank A: MACS1149JD at $z(\text{photo})=9.6$
 - Cycle4 Rank A: MACS0416 #491 at $z(\text{photo})=8.5$
 - (PI: Y.Tamura)