[OIII], [CII] AND DUST OF STAR FORMING GALAXIES IN THE REIONIZATION EPOCH

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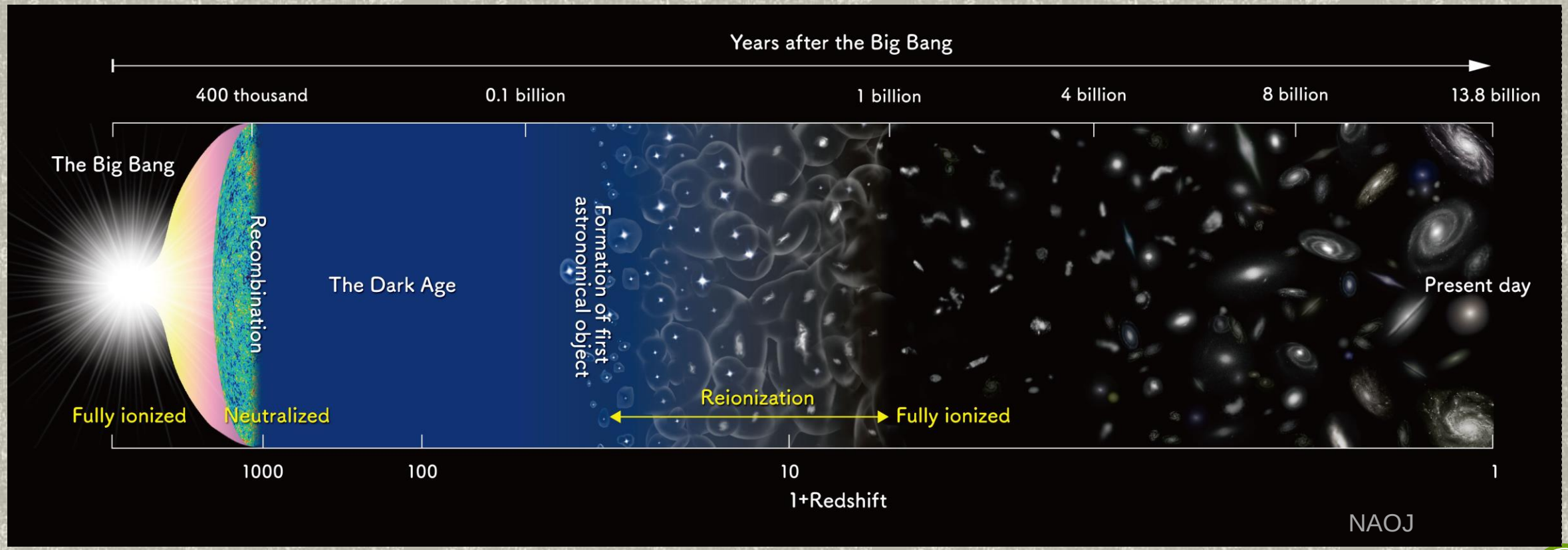
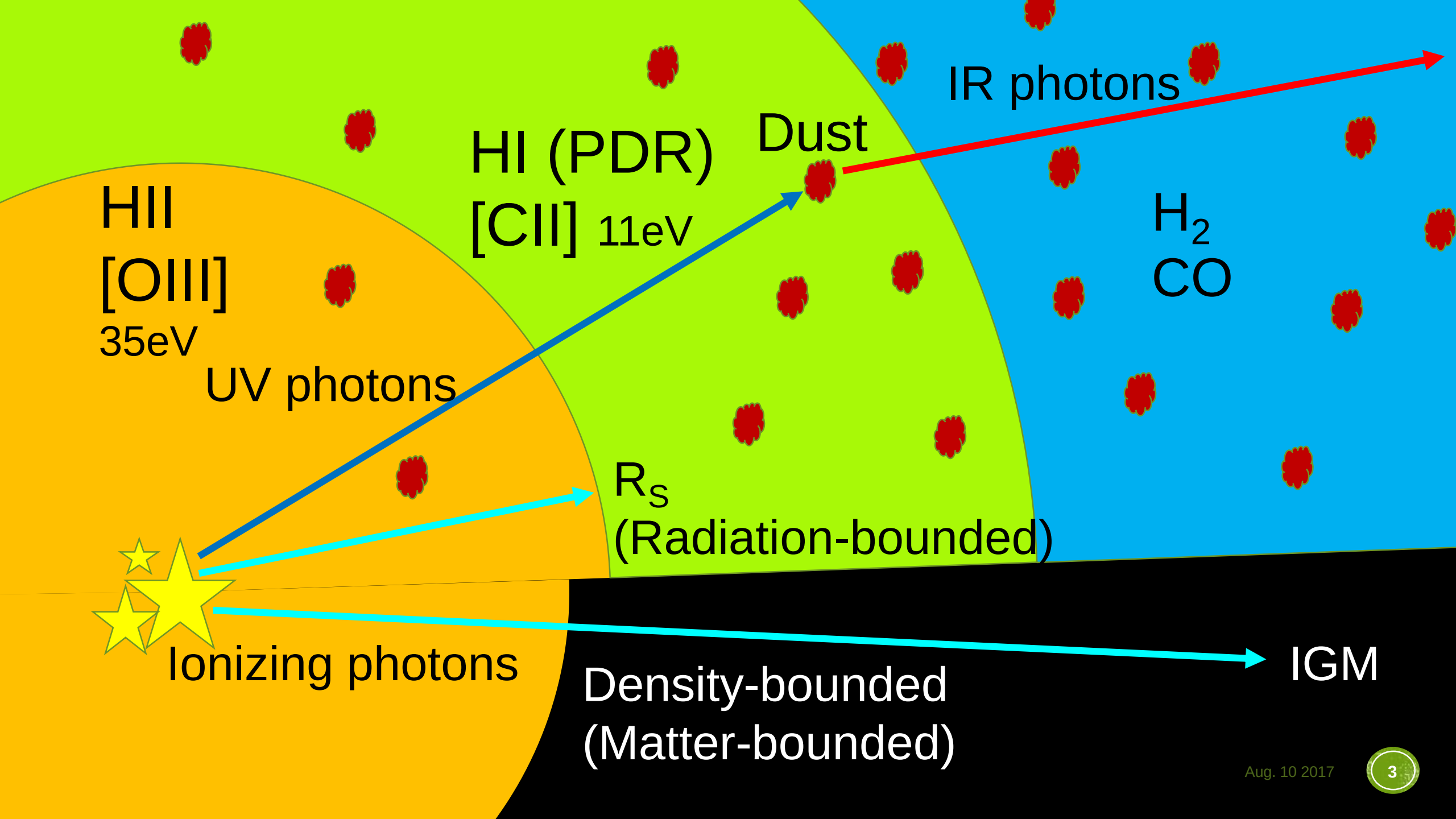
EPOCH OF COSMIC REIONIZATION (EOR)

- The first billion years of the cosmic history: Redshift z~6—20.
- The epoch of the first stars and galaxies' formation.
  - The epoch of the first metal and dust pollution.

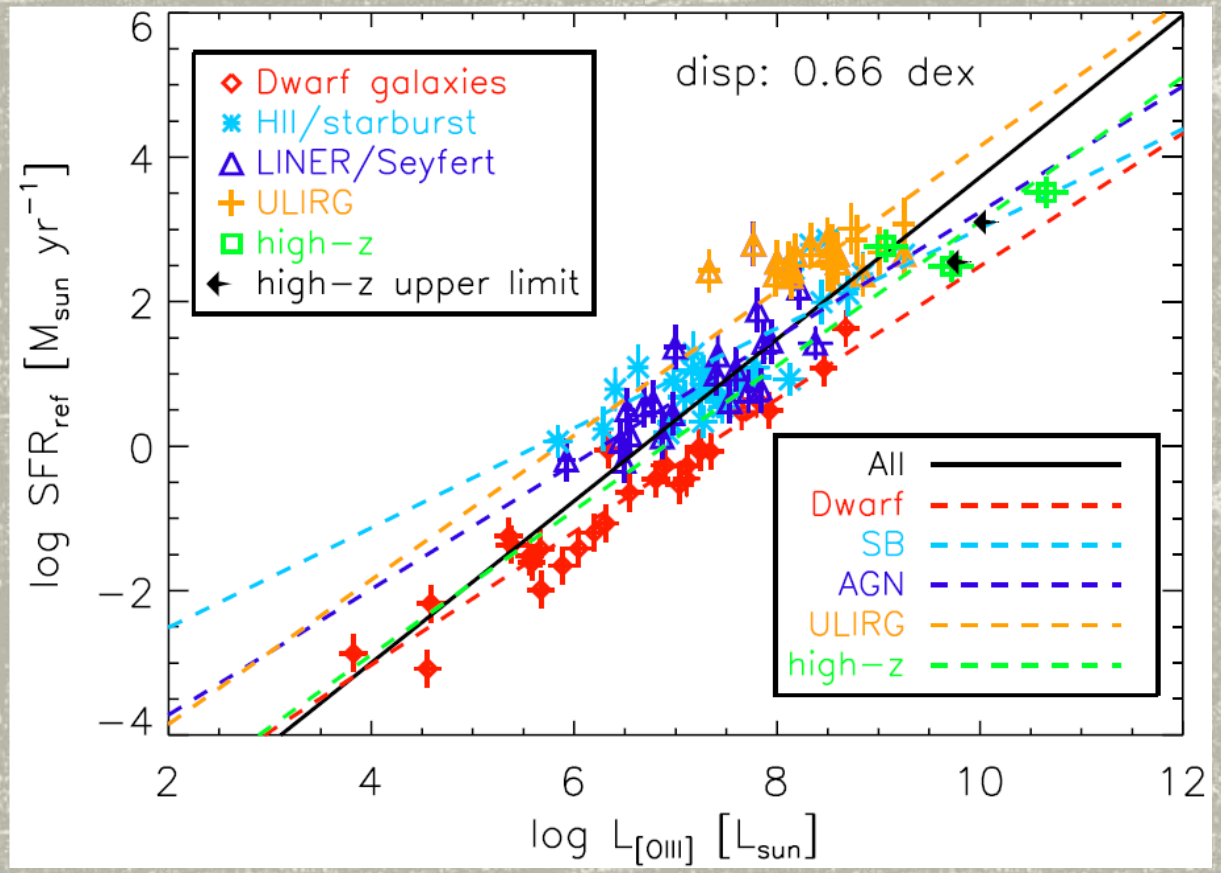



HII
[OIII]
35eV
UV photons
HI (PDR)
[CII] 11eV
Dust
IR photons
H_2
CO
R_S
(Radiation-bounded)
Ionizing photons
Density-bounded
(Matter-bounded)
IGM

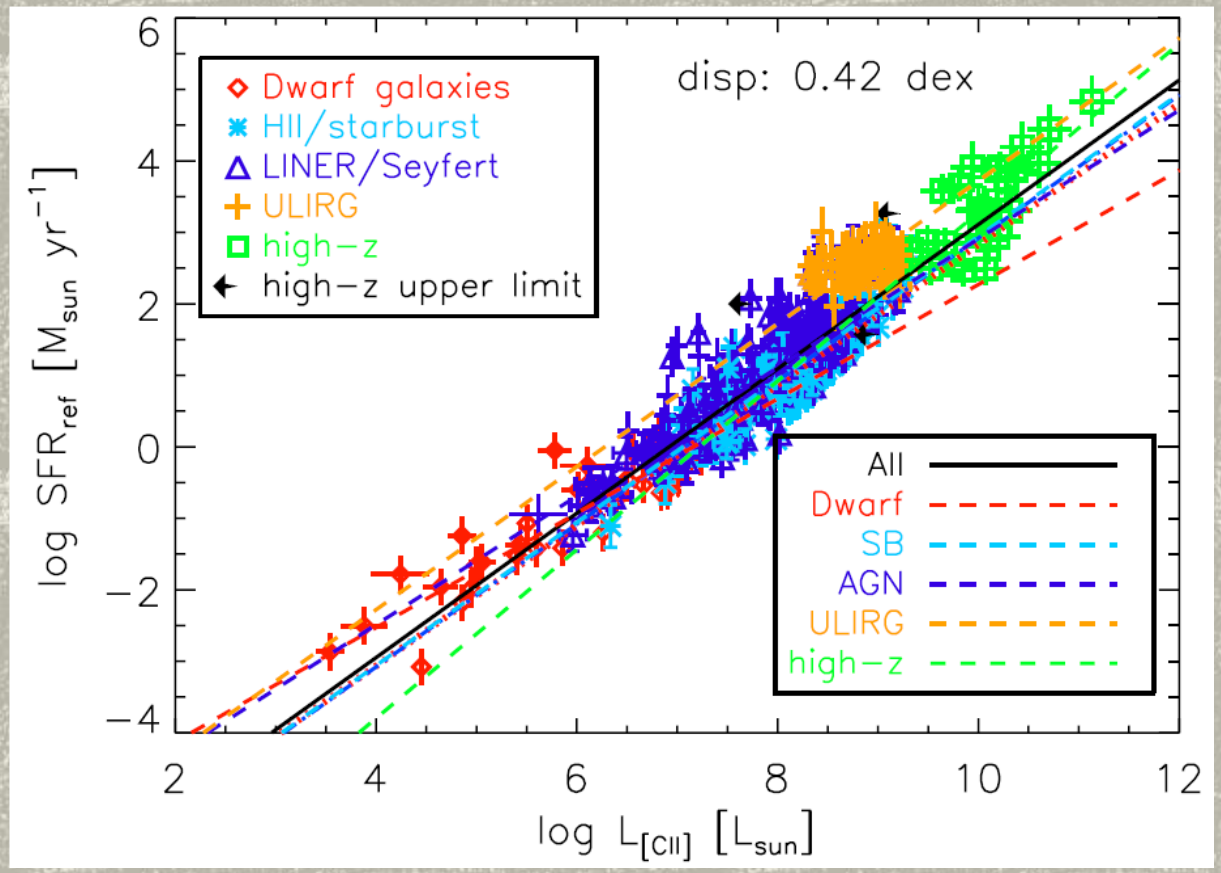
[OIII] & [CII] AS SFR TRACERS

e.g., De Looze+14

SFRref = SFR(UV)+SFR(IR)



[OIII] 88 mic

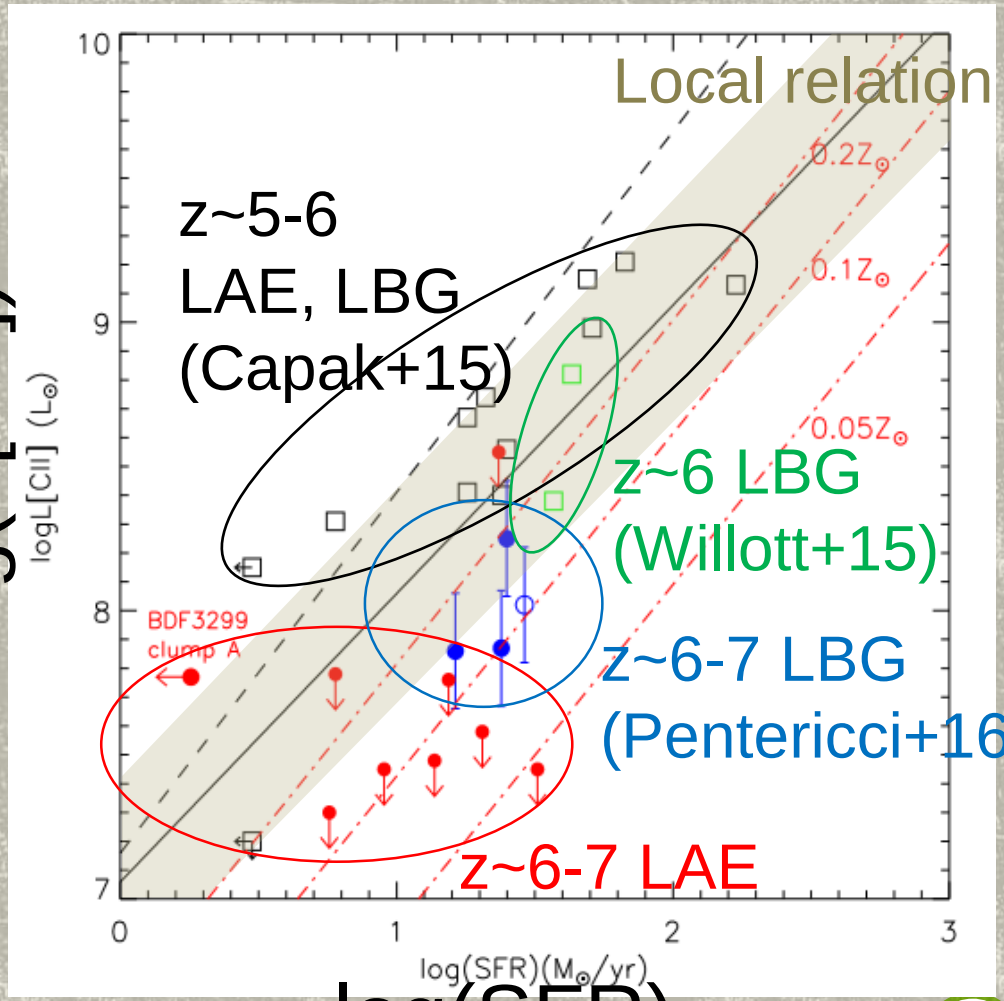


[CII] 158 mic

[CII] 158μm IN EOR: OBSERVATIONS

- Post-EoR galaxies (z<6) seem to emit the [CII] line as strong as local star-forming galaxies.
- The [CII] line from galaxies in EoR (z>6) seems **weak**.
  - An anti-correlation between LyA and [CII]?
  - A spatial offset?
    - Maiolino+15, Pentericci+16
  - [CII] emitting gas without counterparts?
    - Aravena+16

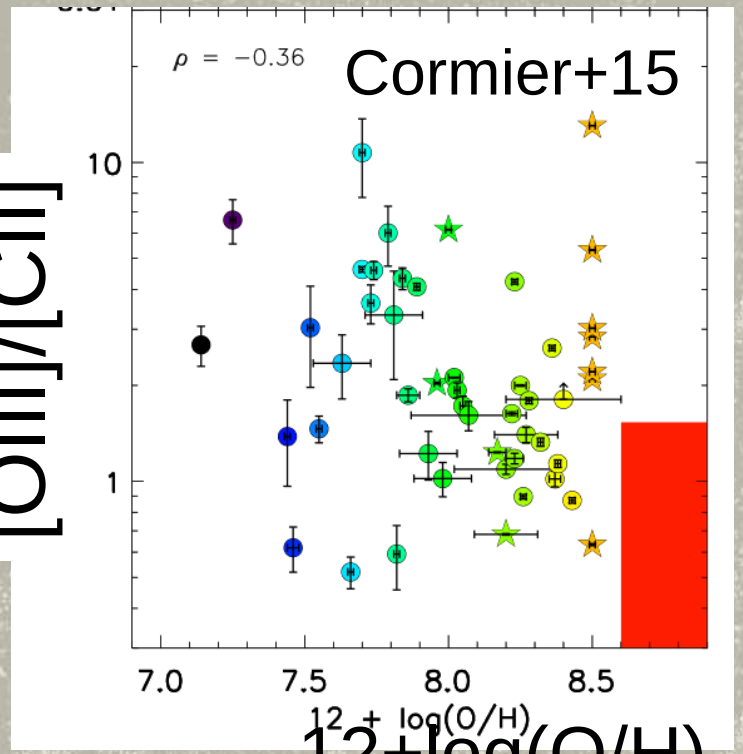
Pentericci+16

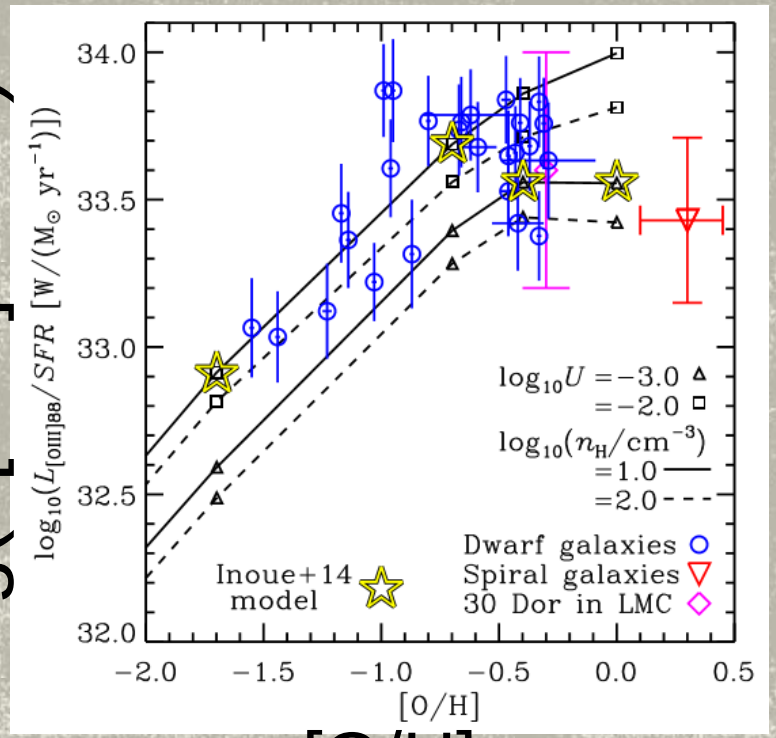


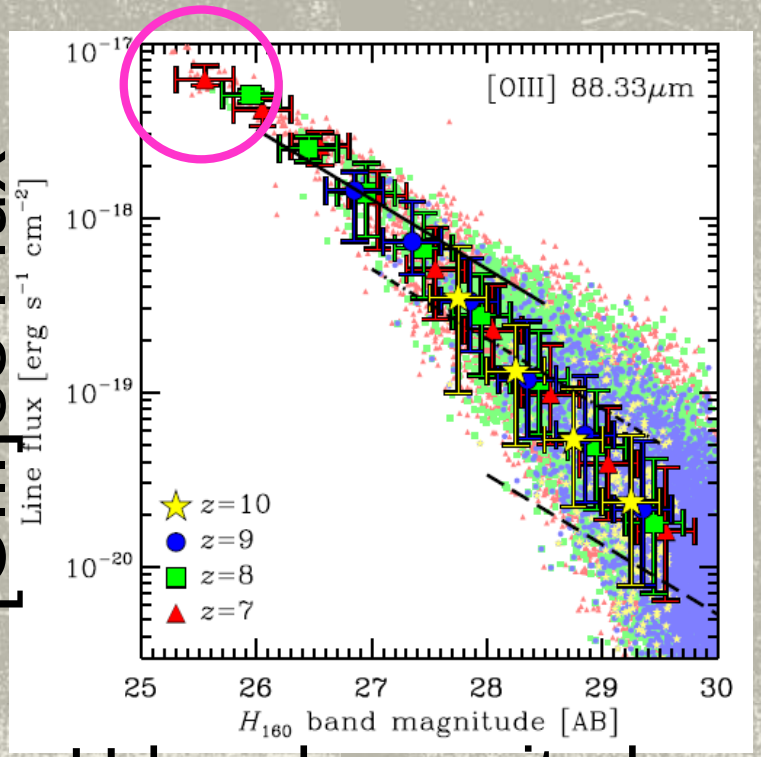
[OIII] 88μm IN EOR: PREDICTION

Inoue+14, ApJL

- Based on Herschel observations of a strong [OIII]88 line in nearby low-metallicity dwarf galaxies, we have predicted that ALMA can detect the [OIII]88 line even in EOR with hydrodynamic simulations (Shimizu+14).



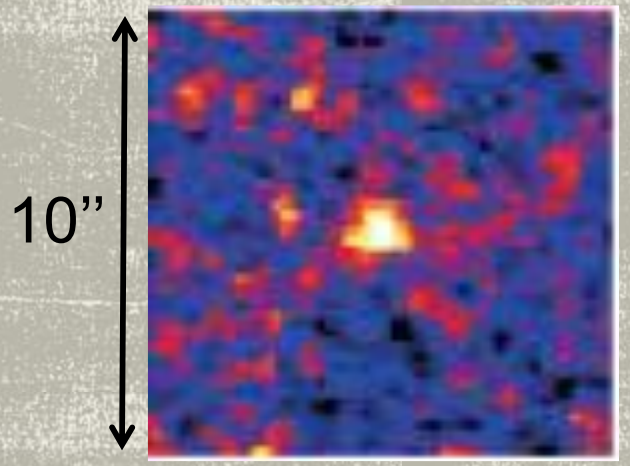




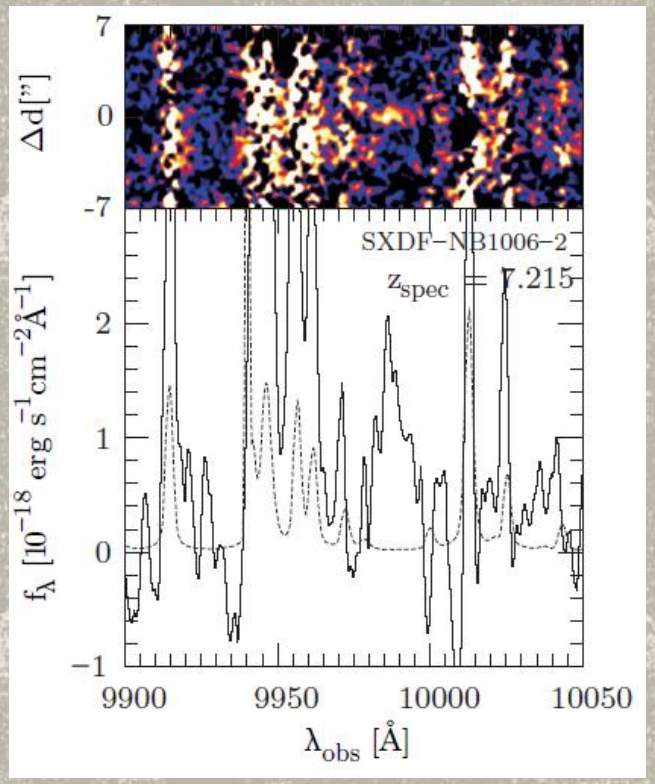
A Z=7.2 STAR-FORMING GALAXY

- SXDF-NB1006-2: an LAE at z(Lyα)=7.215 was found with Subaru (Shibuya+12).
  - The most distant galaxy ever found at that time.
- We observed this object with ALMA in June 2015.
  - Exposure was 2.0 h.

Subaru/NB1006 (14.7 h.)



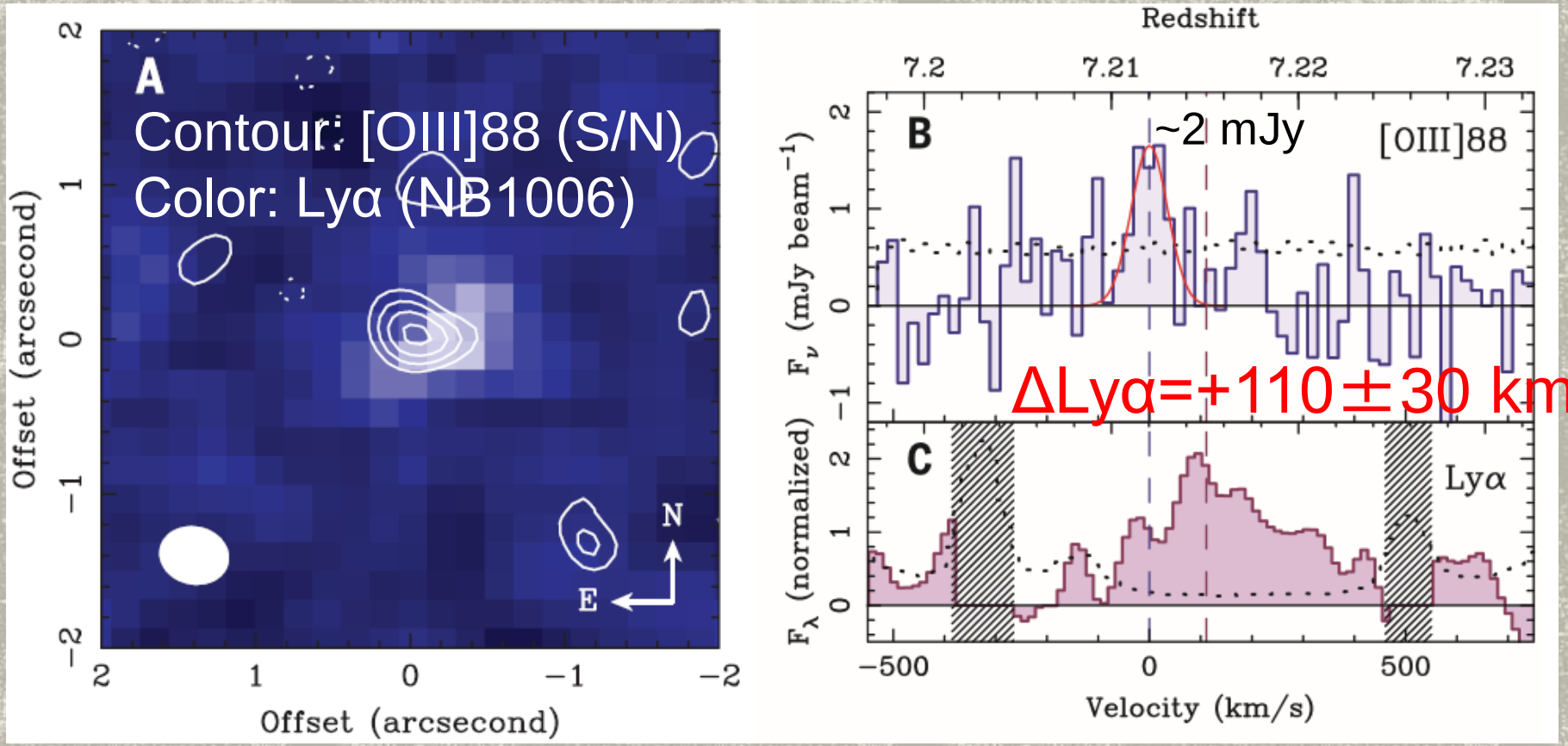
Shibuya+12



Keck/DEIMOS (3.5 h.)

RESULTS OF ALMA OBSERVATIONS

- [OIII] 88 μm emission line was detected (5.3σ).
  - z([OIII])=7.2120 → The most distant oxygen ever found! (in 2016)

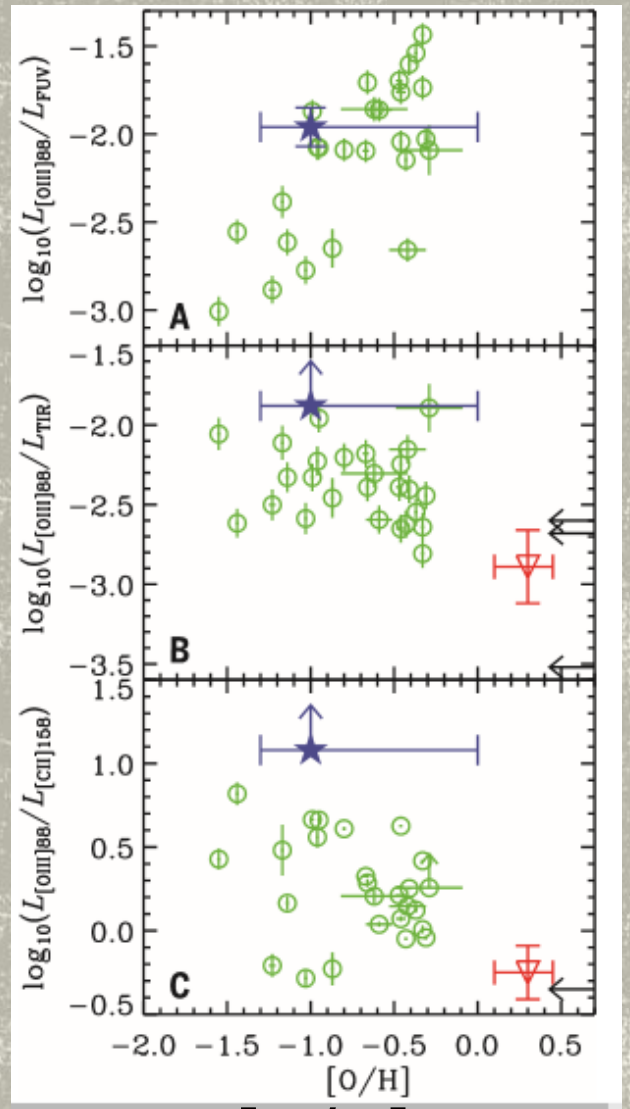


Inoue+16, Science

RESULTS OF ALMA OBSERVATIONS

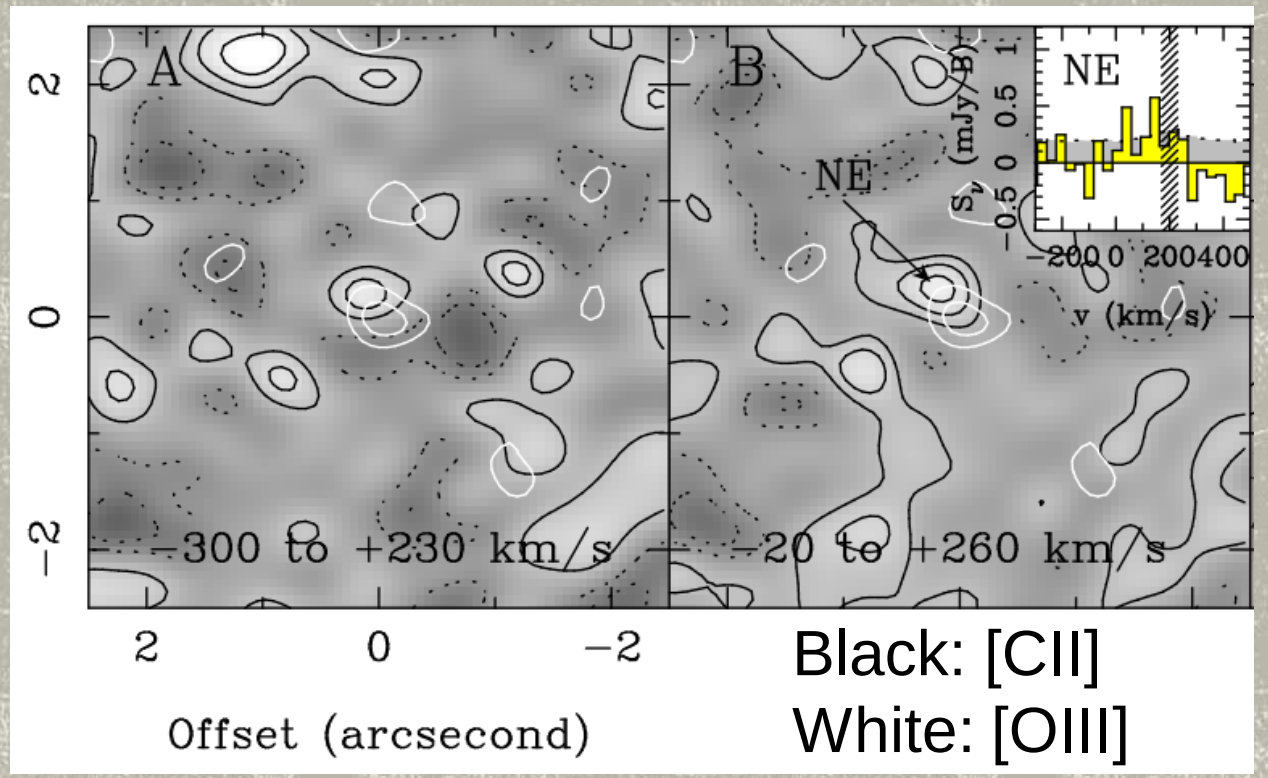
Logarithmic values

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



[O/H]

- No [CII] 158 μm line at the position of the [OIII] line.
- No dust continuum in the two bands.



Inoue+16, Science

DISCUSSIONS: SXDF-NB1006-2 AT Z=7.2

- A small Lyα velocity shift: Δv(Lyα)=+110±30 km/s

  → N_HI<1e20 cm-2 (Shibuya+14, Hashimoto+13,15)

- A high [OIII]/[CII] ratio (weak [CII]): [OIII]/[CII]>12

  → Little amount of cool HI gas emitting [CII]

- A low dust-to-metal ratio: <20%

  → Efficient dust destruction by SNe or inefficient dust mass growth in the dense ISM (lack of dense gas?)

An unusually small amount of HI gas in the ISM may enhance the escape fraction of ionizing photons (fesc).

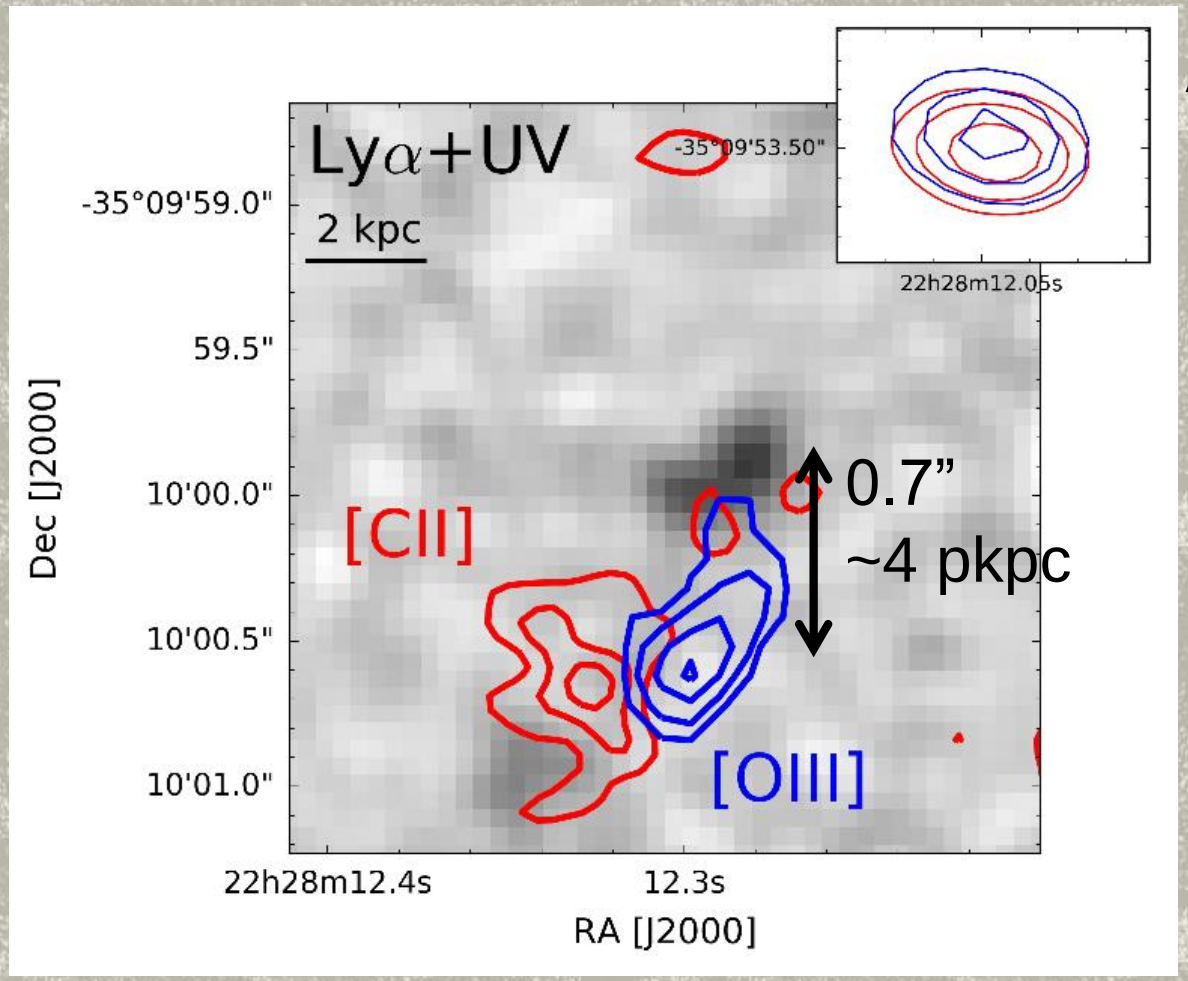
- The SED fitting favors a high fesc~0.5.
  - A prototype of galaxies which ionized the IGM?

Density-bounded?

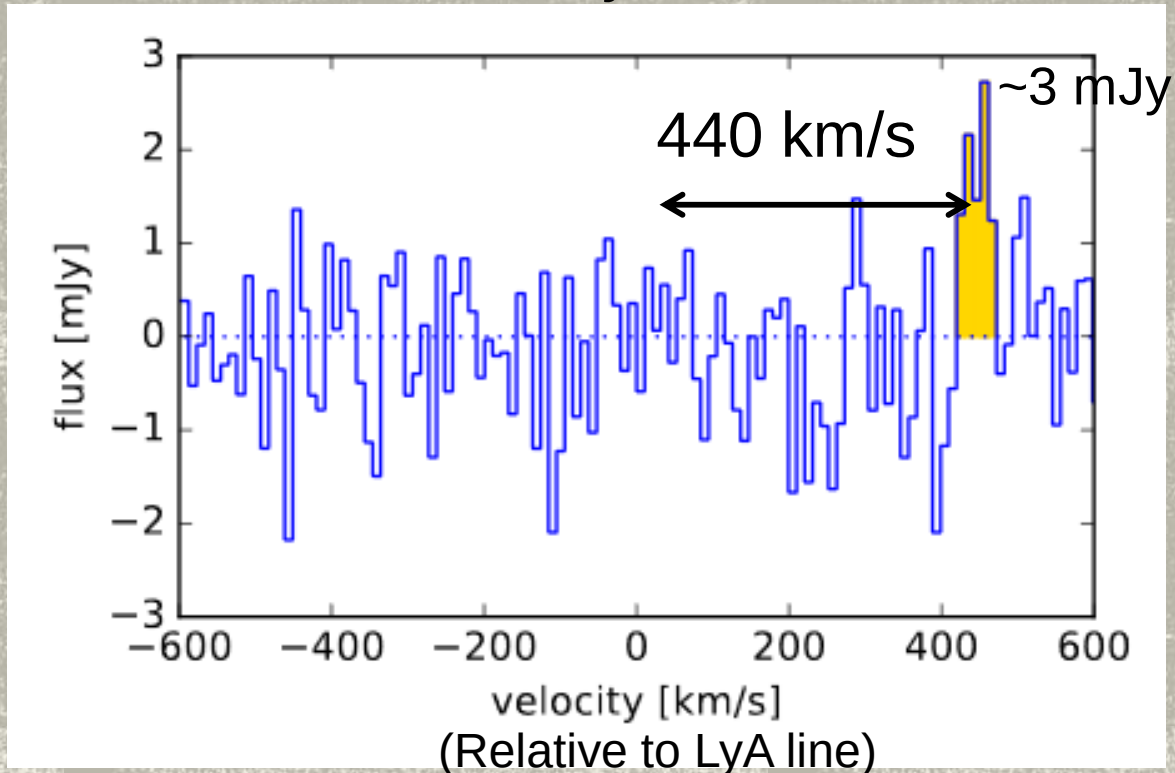
Inoue+16, Science

ANOTHER [OIII] 88μm DETECTION AT Z=7.1

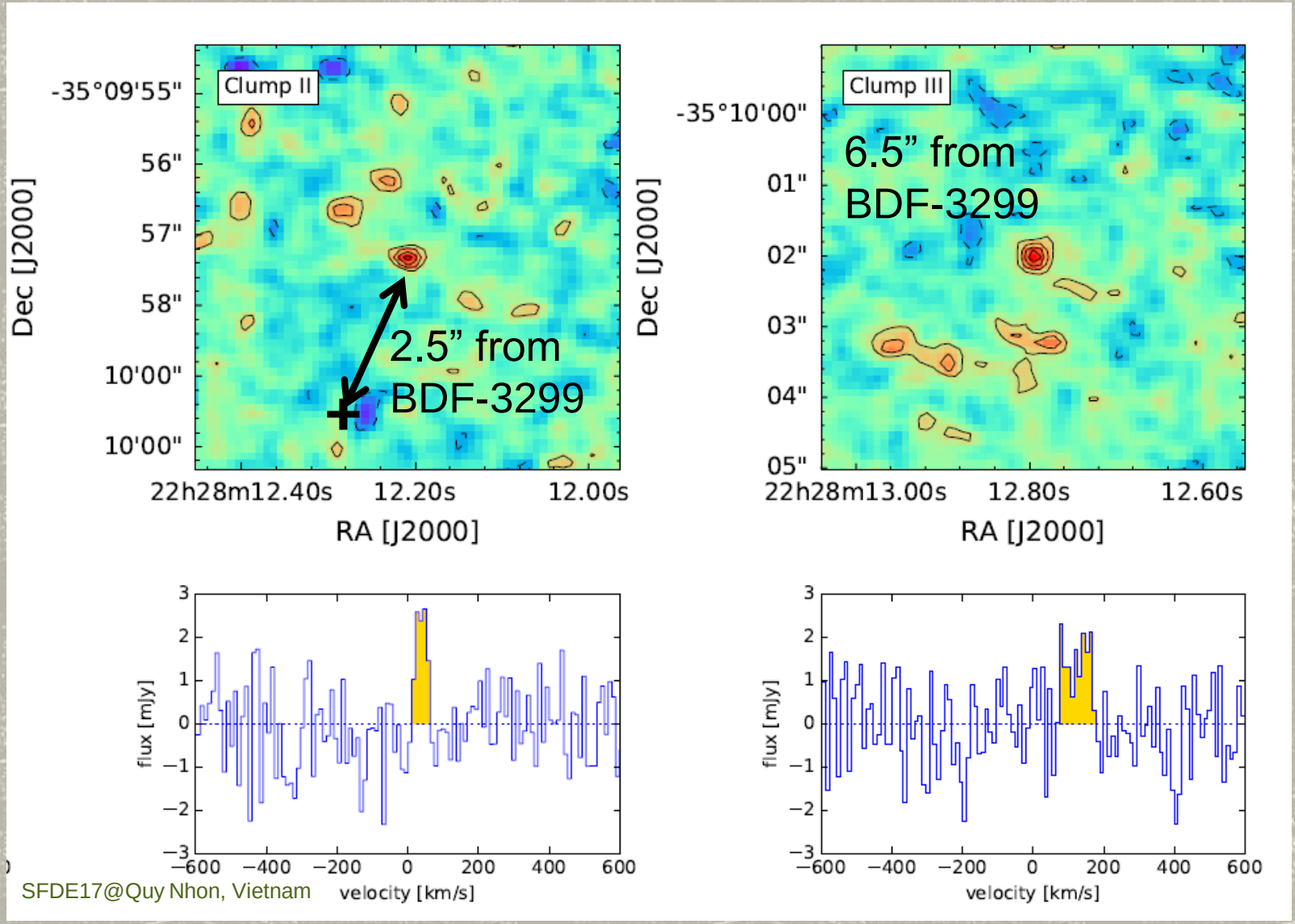
- Carniani et al. 2017 for BDF-3299



ALMA Bands 6 and 8 astrometric consistency



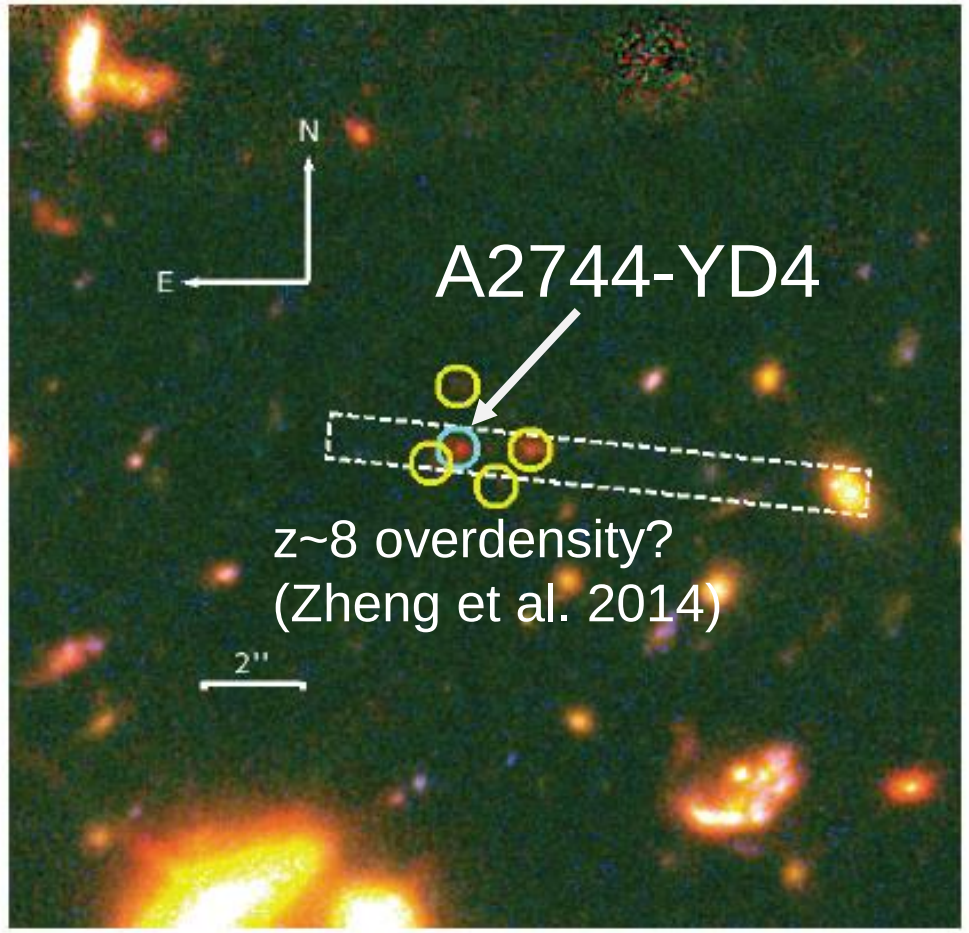
[OIII] 88μm LINE EMITTERS AT Z=7.1?

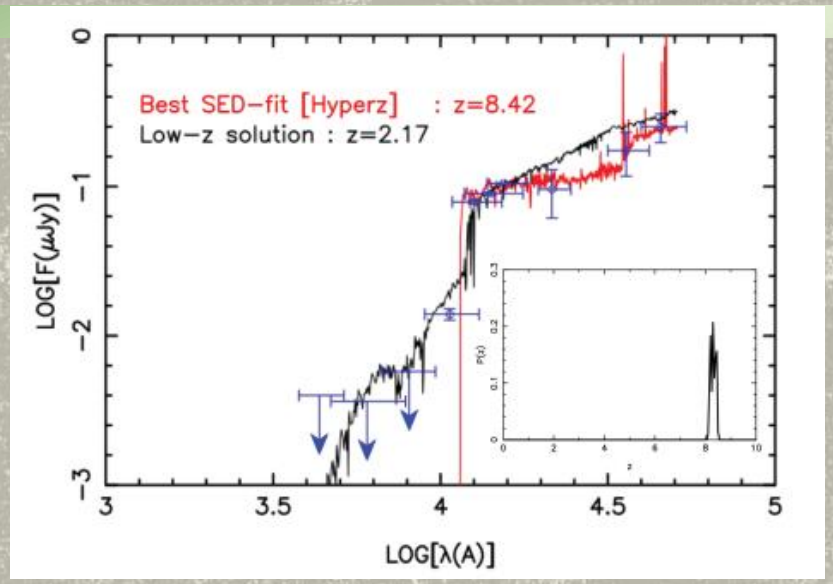


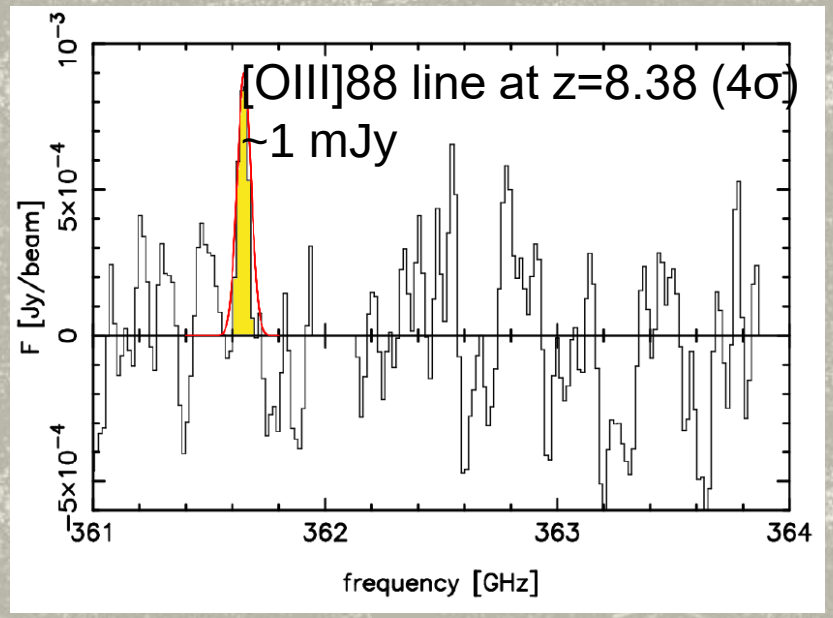
Carniani et al. 2017
No counterpart so far.
BDF-3299 is in fact in an overdensity region (Castellano+16)!
The number density of [OIII] emitters should be very high (they did not show the number).

THIRD DETECTION CAME OUT AT Z=8.4!?

- Laporte et al. 2017







Detections of LyA and [OIII]88 lines in addition to dust continuum!

CY3 DDT: SXDF-NB1006-2 [OIII] HIGH-RES.

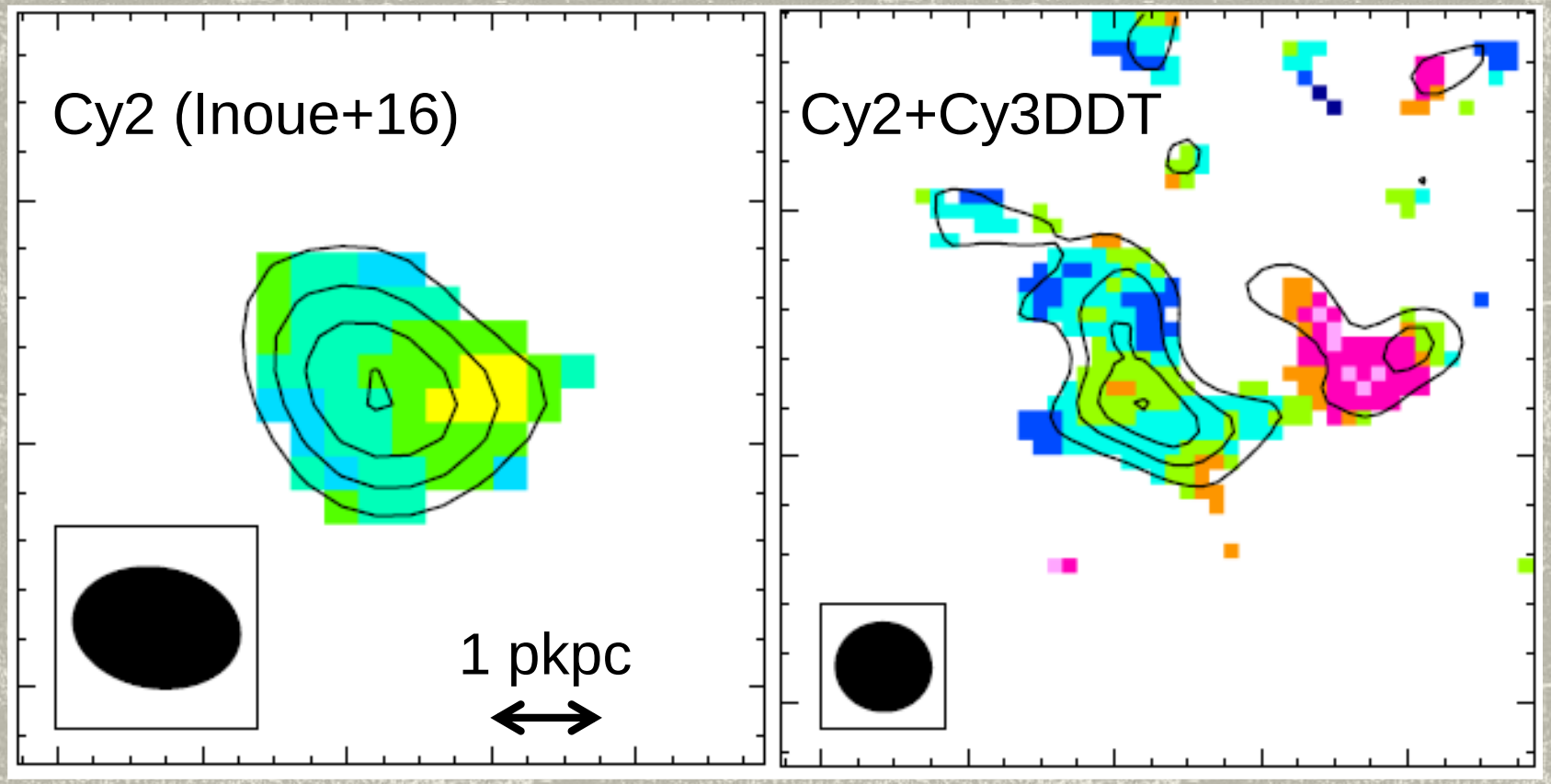
Urata, Tamura, AKI, + in prep.

- The [OIII] line was resolved-out in 0.1” resolution observations.

→ The line comes from extended ionized gas.

- Possible redshifted component

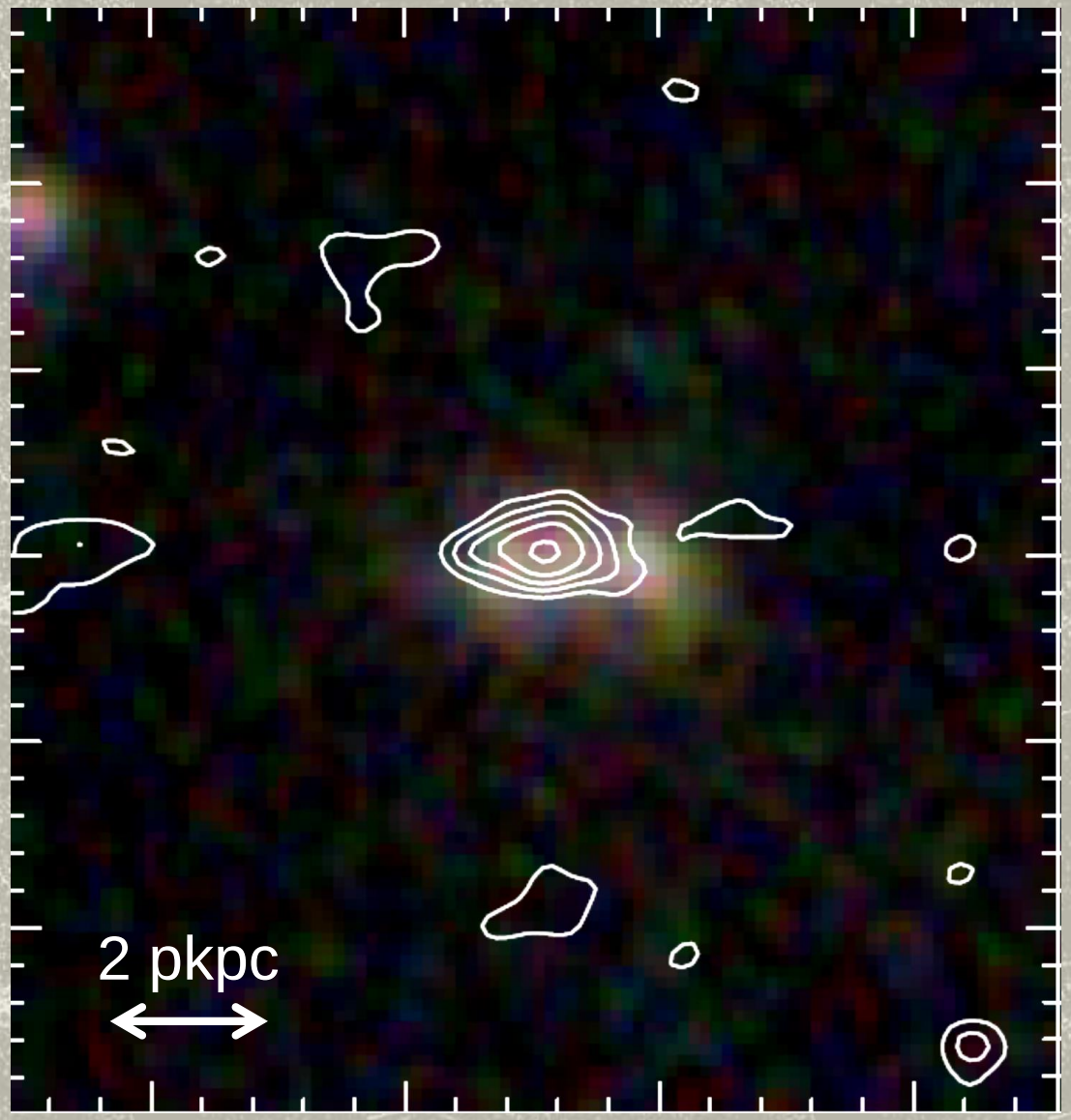
→ outflow?



CY4: ANOTHER Z>8 DUST!

Tamura, AKI, + in prep.

- Photometric z=8.5
- 6σ continuum detection in Band7
- L(IR)~2e11 Lsun (40K, β=1.5)
- Mdust~1e7 Msun



Contour: Dust continuum
Background: HST false-color image
F814W (Blue), F105W (Green), F160W (Red)

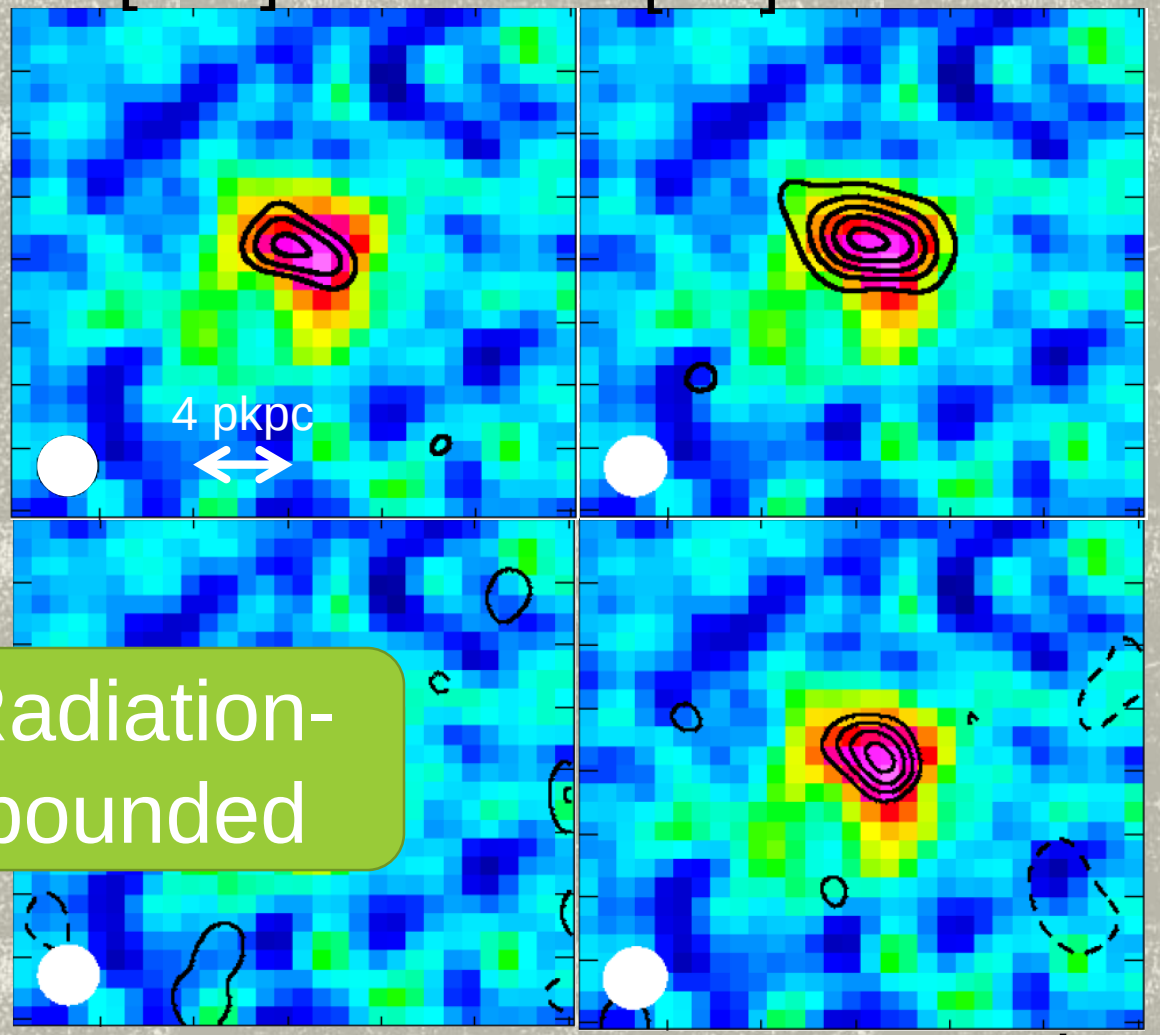
CY4: COMPLETE OF THE "THREE" AT Z=7.2!

Hashimoto, AKI, + in prep.

- LyA at z=7.1702
- [OIII]88: 8σ at z=7.1517
- [CII]158: 10σ at z=7.1518
  - [OIII]/[CII]=2.1
  - Δv(LyA)=677 km/s

  → High N(HI) → low fesc
- Dust (Band6) 5σ

Contour:
ALMA lines 3, 4, 5, …xσ
ALMA continua 2, 3, 4, …xσ
Background: UVISTA H-band



SUMMARY

- FIR [OIII] and [CII] lines are powerful tools to probe SF in young galaxies in the EoR as well as in the nearby Universe.
- The [OIII] 88 micron line is already detected in several galaxies in the EoR.
- These galaxies are diverse:
  - A strong [OIII] but neither [CII] nor dust → Highly ionized ISM (density-bounded?) → possible “ionizer”
  - [OIII], [CII] and dust detected → more normal radiation-bounded?
  - Spatially offset [OIII] and [CII] lines
  - Dust and [OIII] line (but no [CII] observation yet) at z>8