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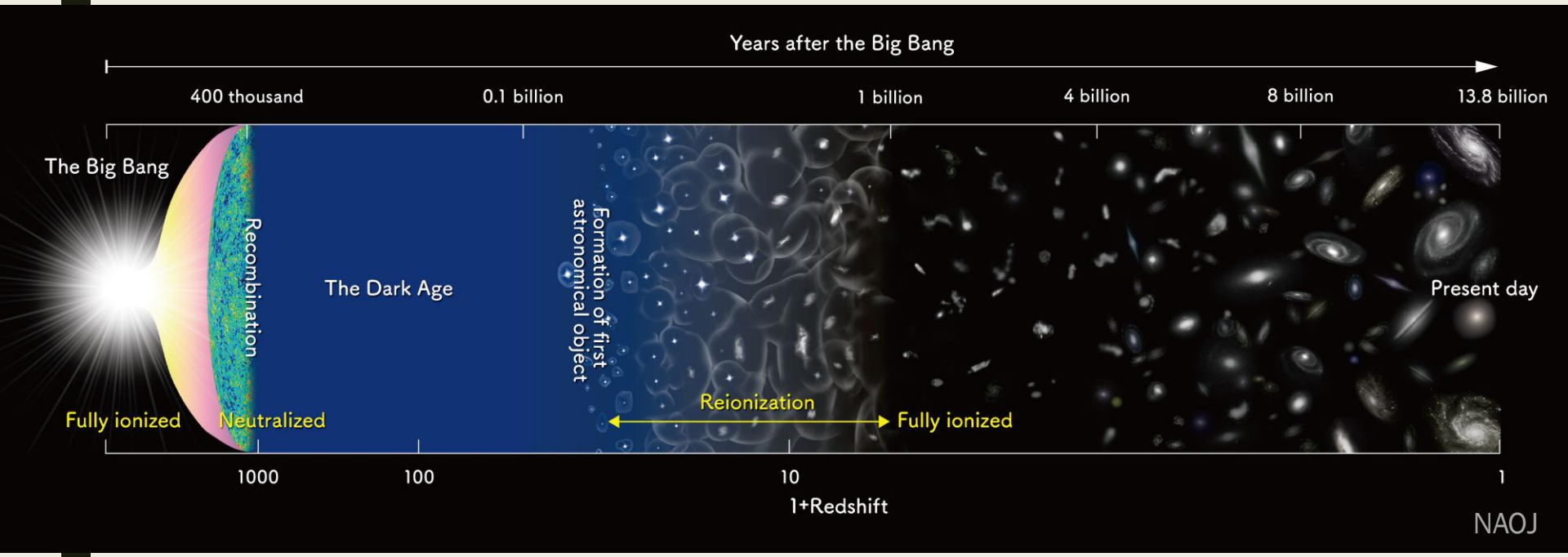
THE FIR [OIII]-TO-[CII] LINE RATIO OF GALAXIES IN THE REIONIZATION EPOCH AND THEIR ESCAPE FRACTION

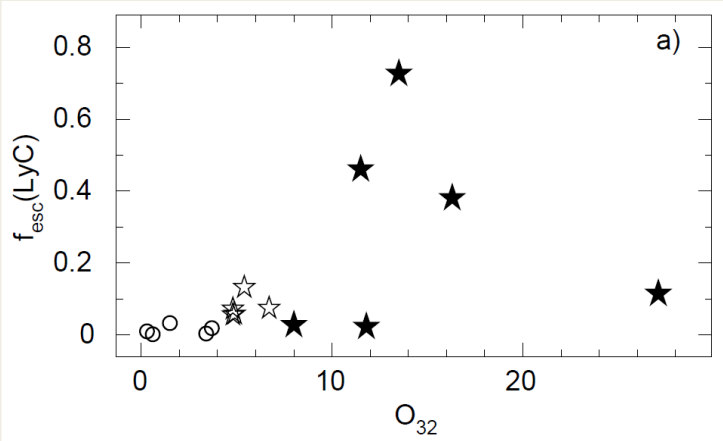
Epoch of Cosmic Reionization

- The first billion years of the cosmic history.
  - *Redshift z>6 (e.g., Planck2018: z=7.7±0.7)*
- The epoch of the first stars and galaxies' formation.
  - *The epoch of the first element & dust formation.*
- What kind of objects caused reionization?



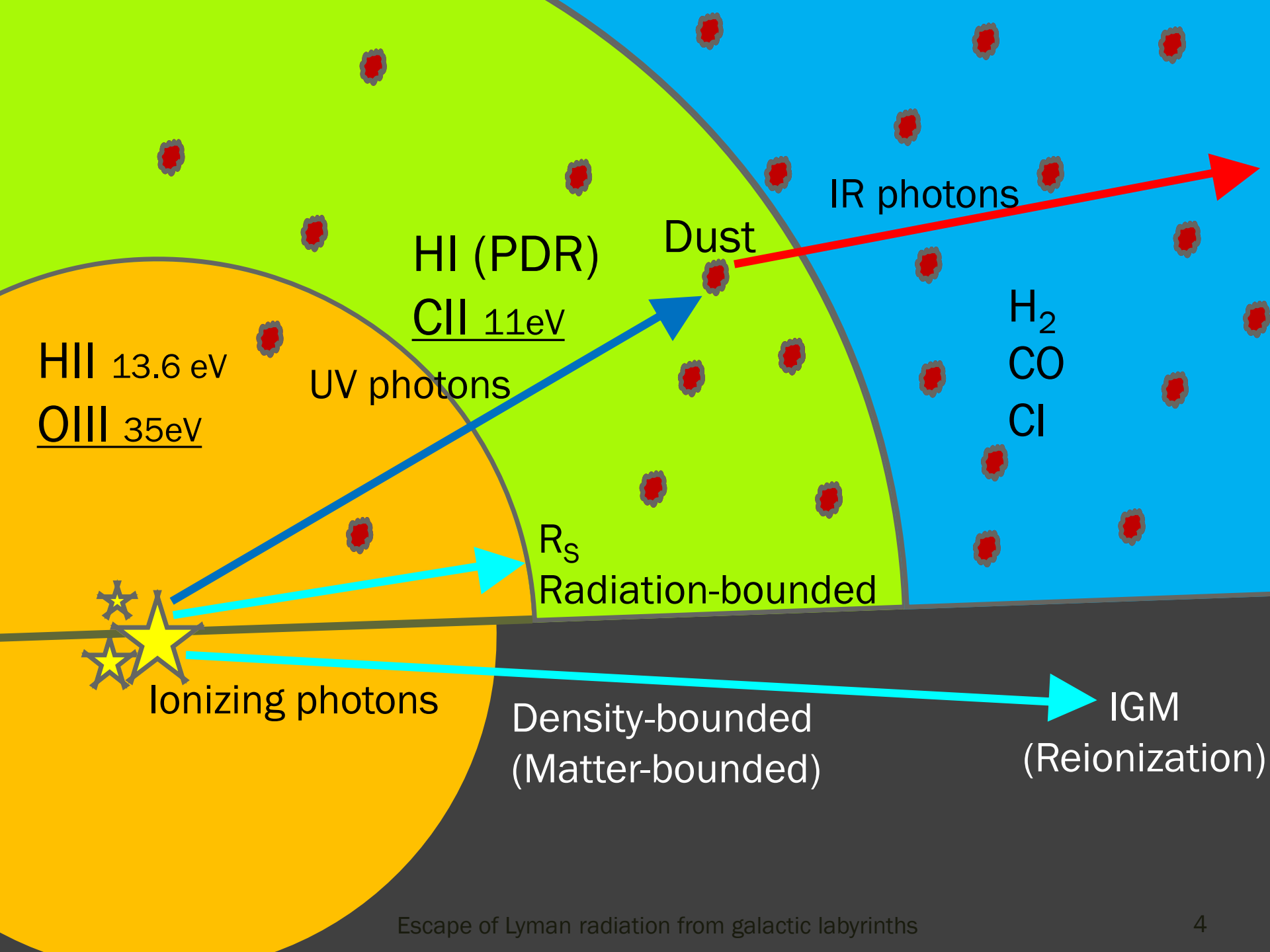
Emission line ratios as LyC indicators

- High [OIII]/[OII] (e.g., Nakajima & Ouchi 14)
  - *Successful in the local Universe (e.g., Izotov+16,18)*
  - *Verifying at z~3 (e.g., Naidu+18, Fletcher+18)*
  - *Waiting for JWST in the EoR…*



Izotov+18

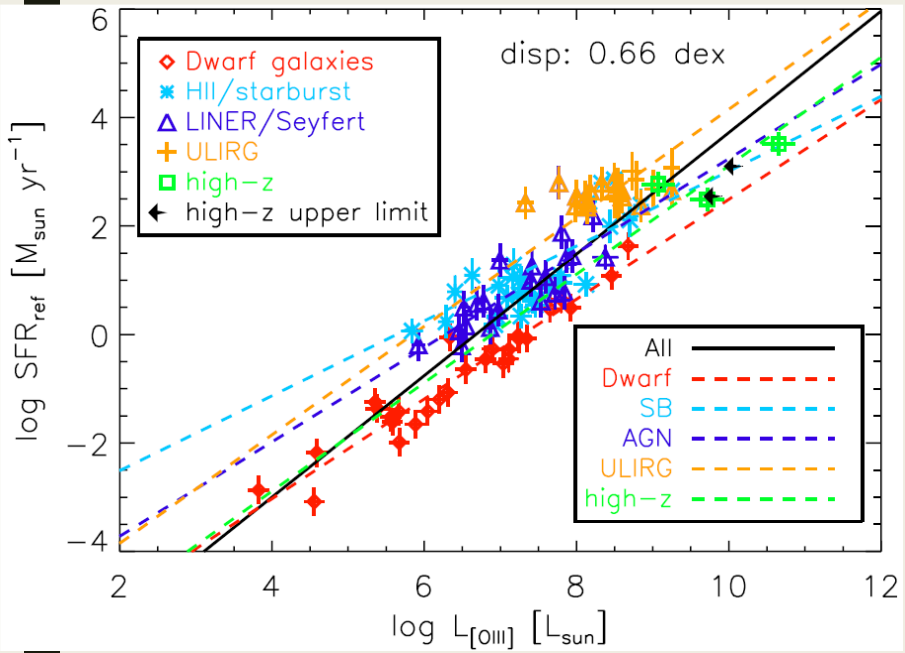
- Other line ratios currently available in the EoR?
  - *FIR [OIII]/[CII] ?*


IR photons
Dust
HI (PDR)
CII 11eV
H_2
CO
CI
HII 13.6 eV
OIII 35eV
UV photons
R_S
Radiation-bounded
Ionizing photons
Density-bounded
(Matter-bounded)
IGM
(Reionization)

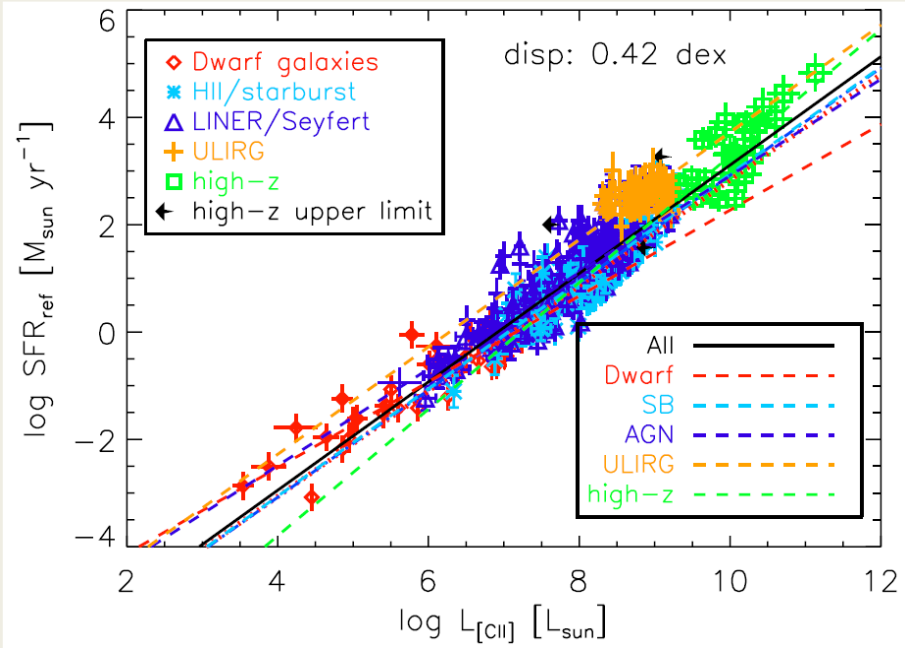
[OIII]88 & [CII]158 as SFR tracers

e.g., De Looze+14

SFRref = SFR(UV)+SFR(IR)



[OIII] 88 mic

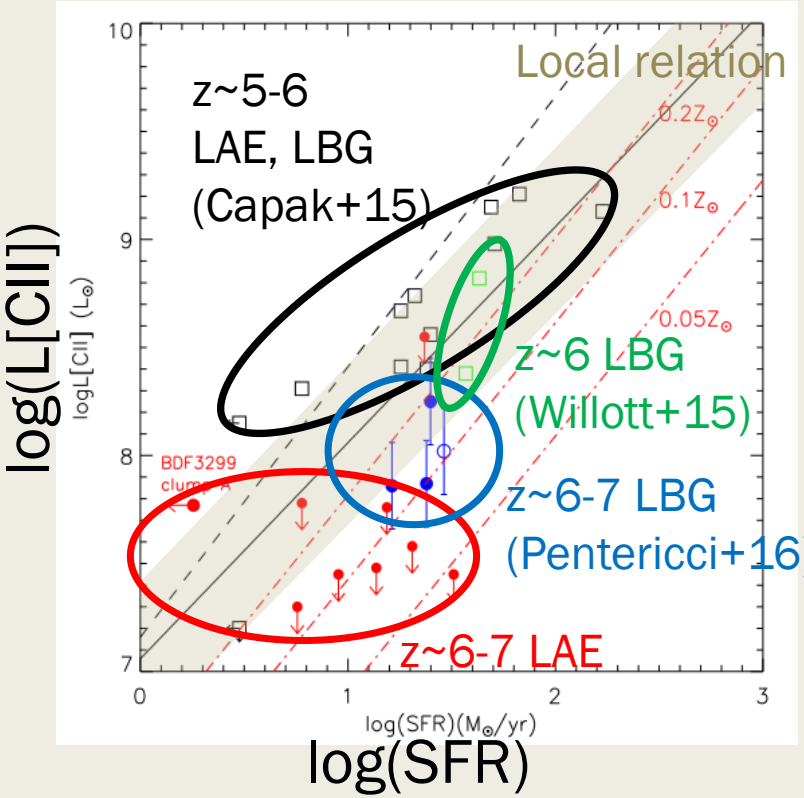


[CII] 158 mic

[CII] 158μm in EOR: observations

- Post-EoR galaxies (z<6) seem to be as strong in [CII] as local star-forming galaxies.
- The [CII] line from galaxies in EoR (z>6) seems **weak.**
  - *An anti-correlation between LyA and [CII]*
    - Harikane+18

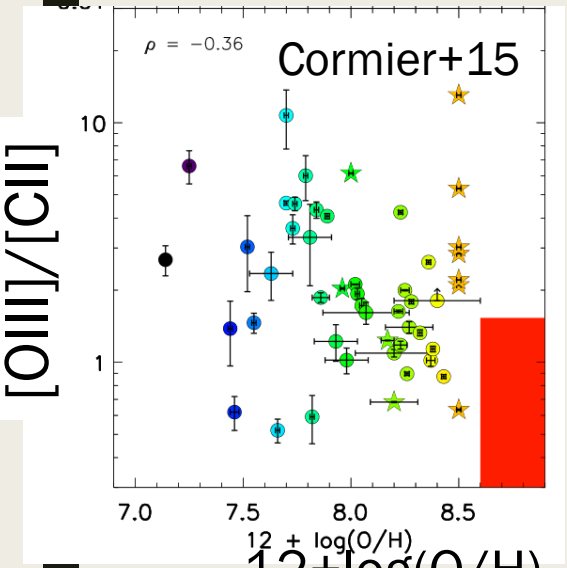
Pentericci+16

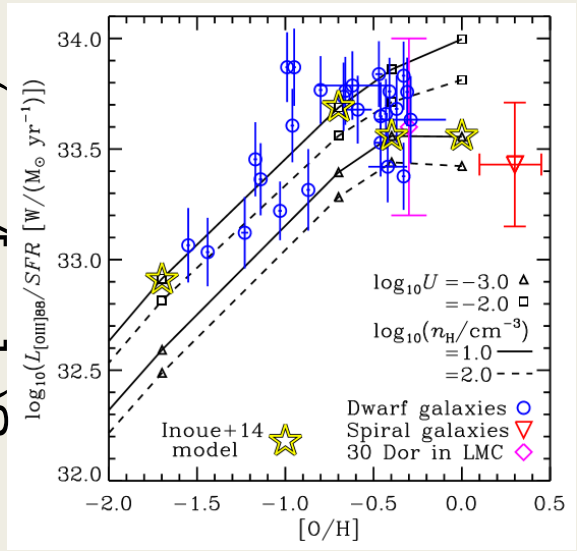


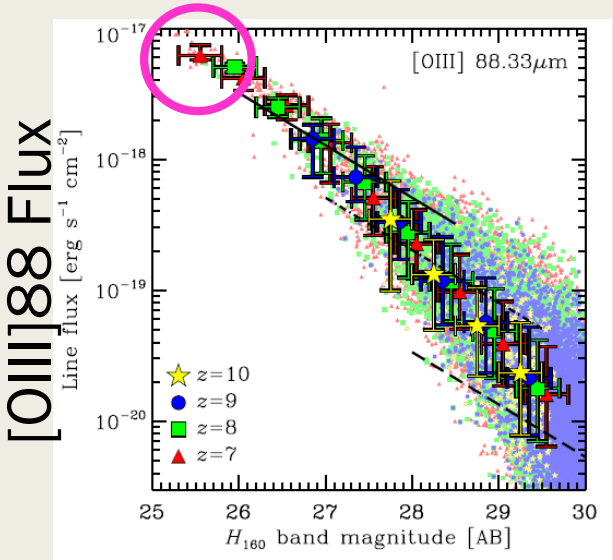
AKInoue+14, ApJL

[OIII] 88μm in EOR: prediction

- 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).



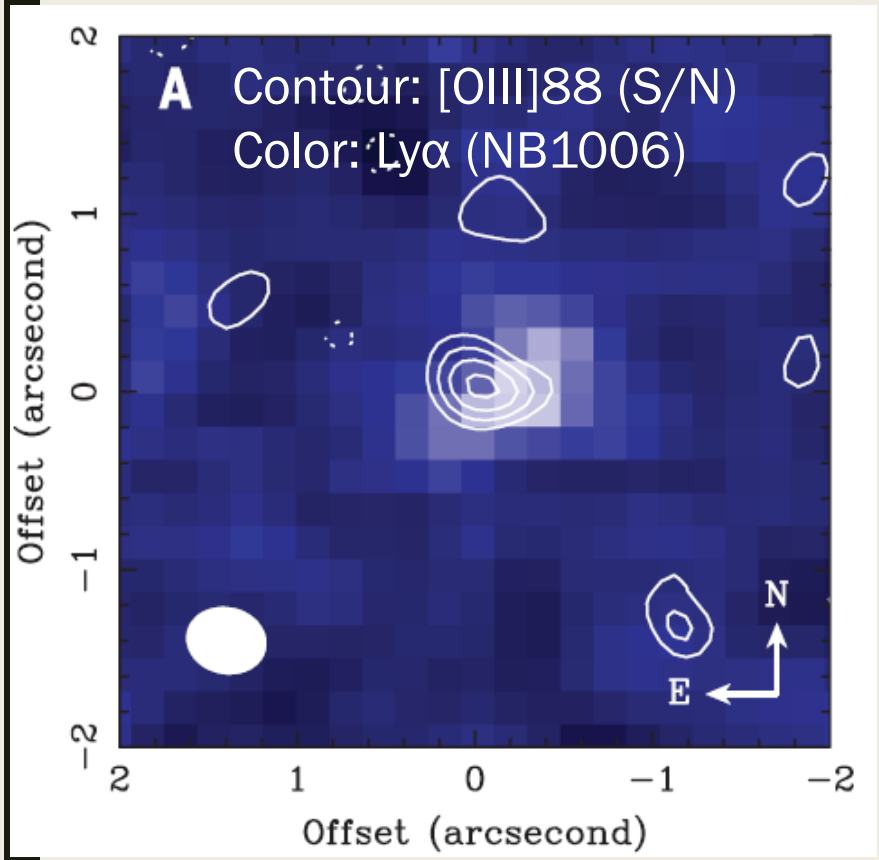


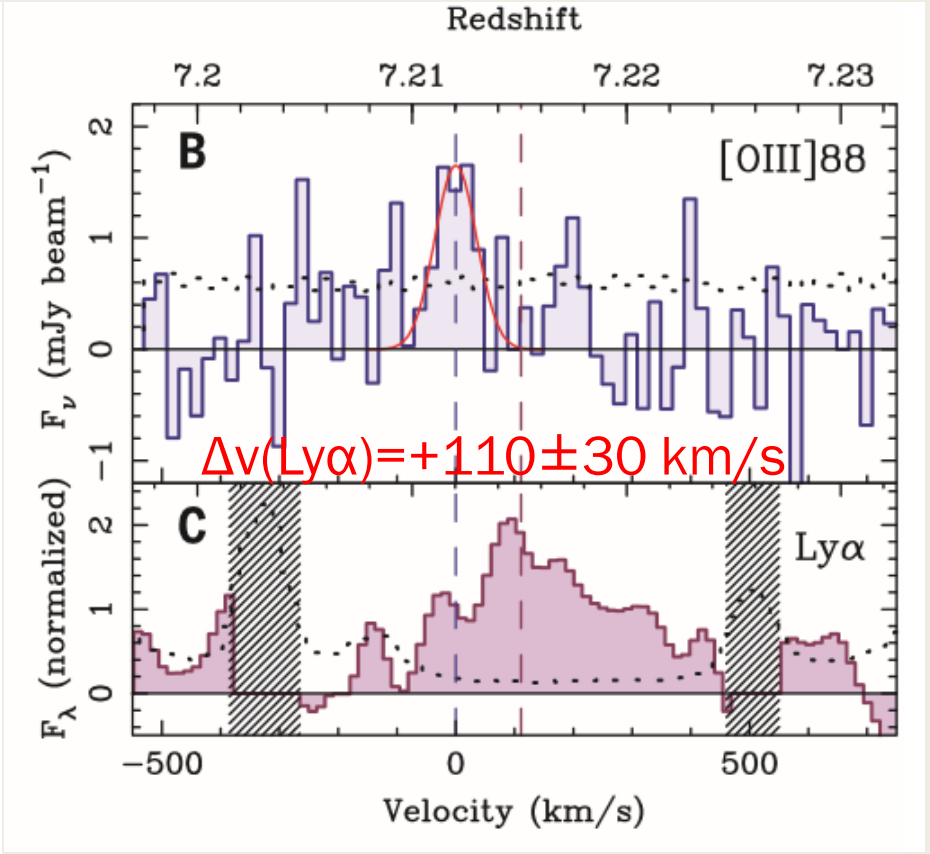


AKInoue+16, Science

SXDF-NB1006-2

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

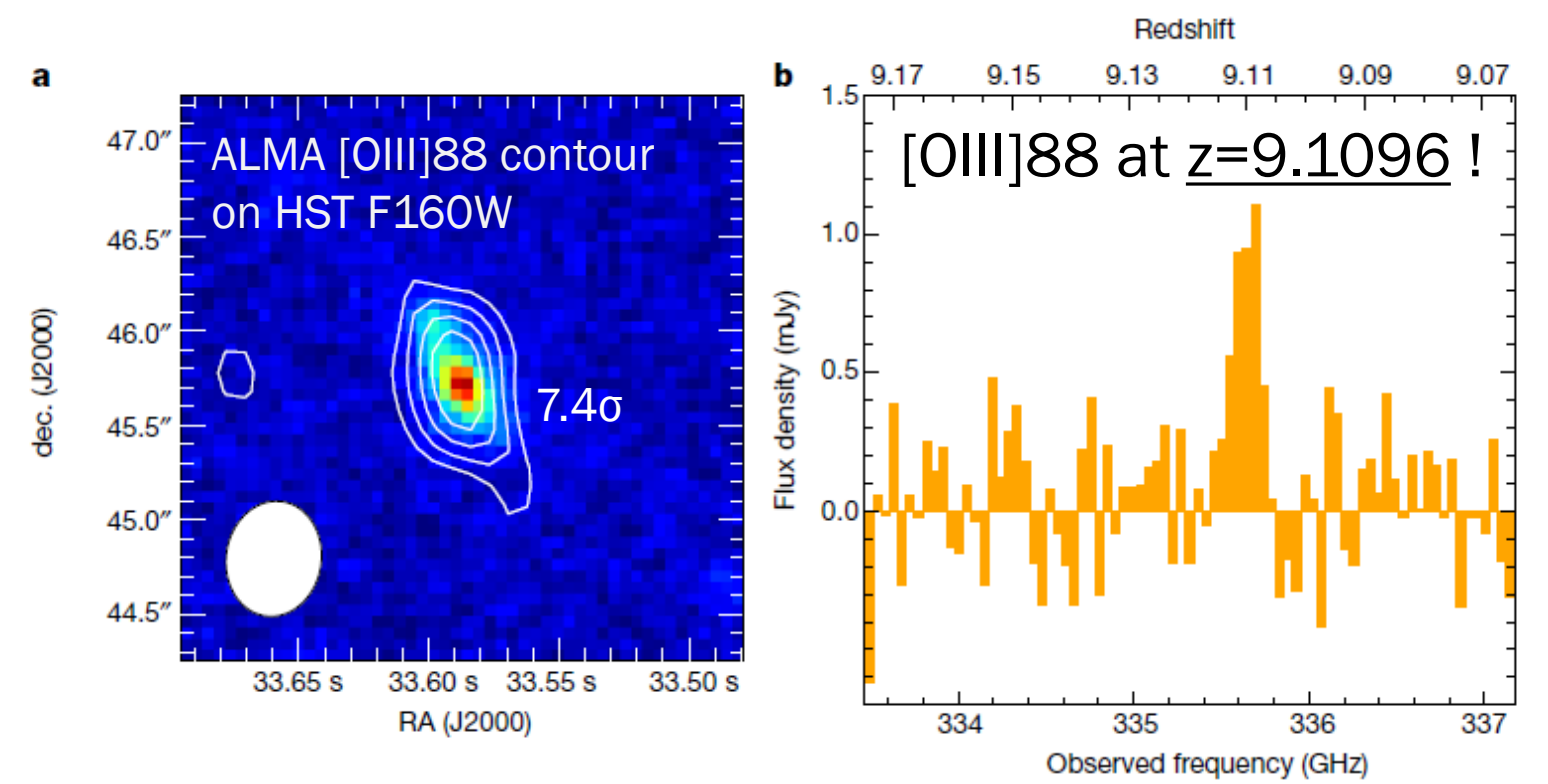




Hashimoto+AKI+18a, Nature

MACS1149-JD1

- [OIII] 88 μm line was detected at 7.4σ
  - *The new spectroscopic redshift record !*

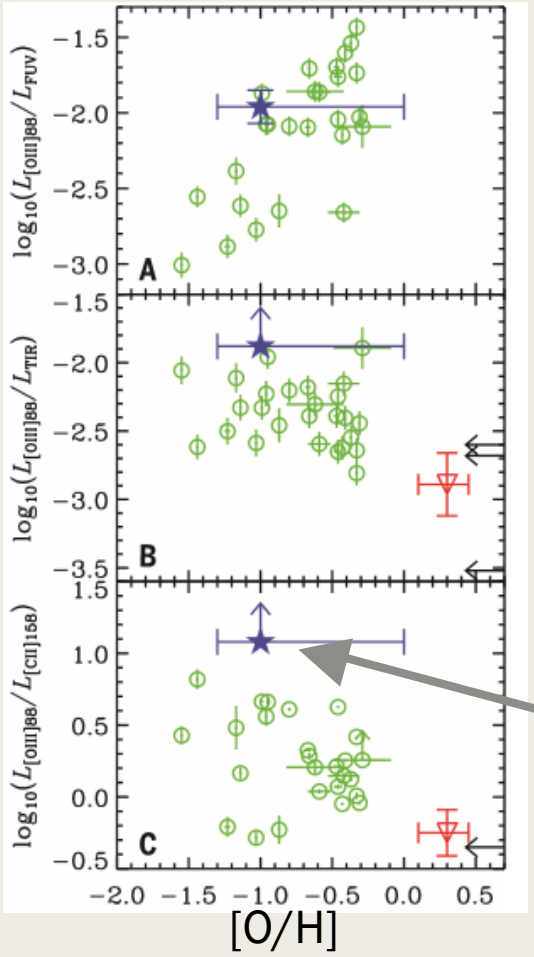


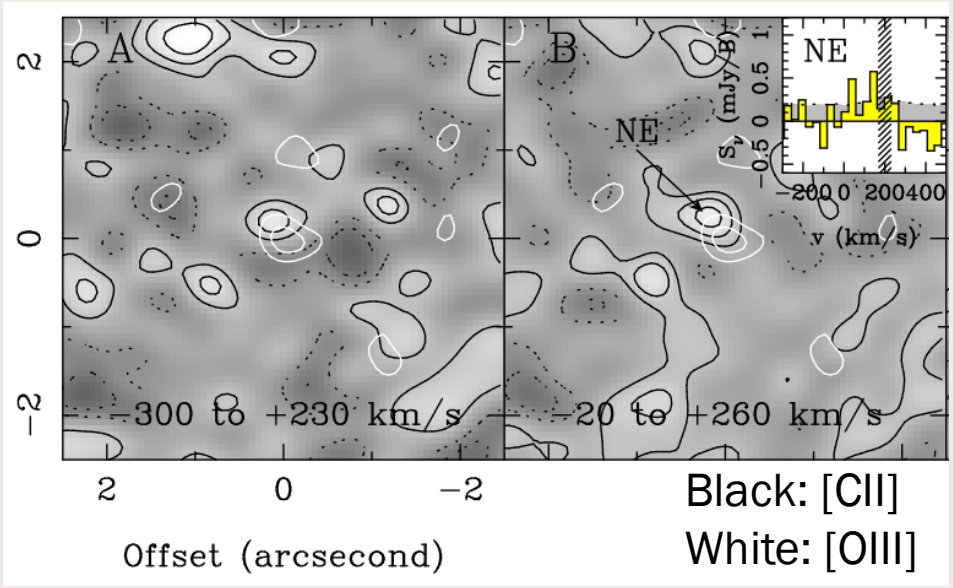
So far, ~10 galaxies/QSOs at z>6 were observed and the line was always detected !

AKInoue+16, Science

SXDF-NB1006-2

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





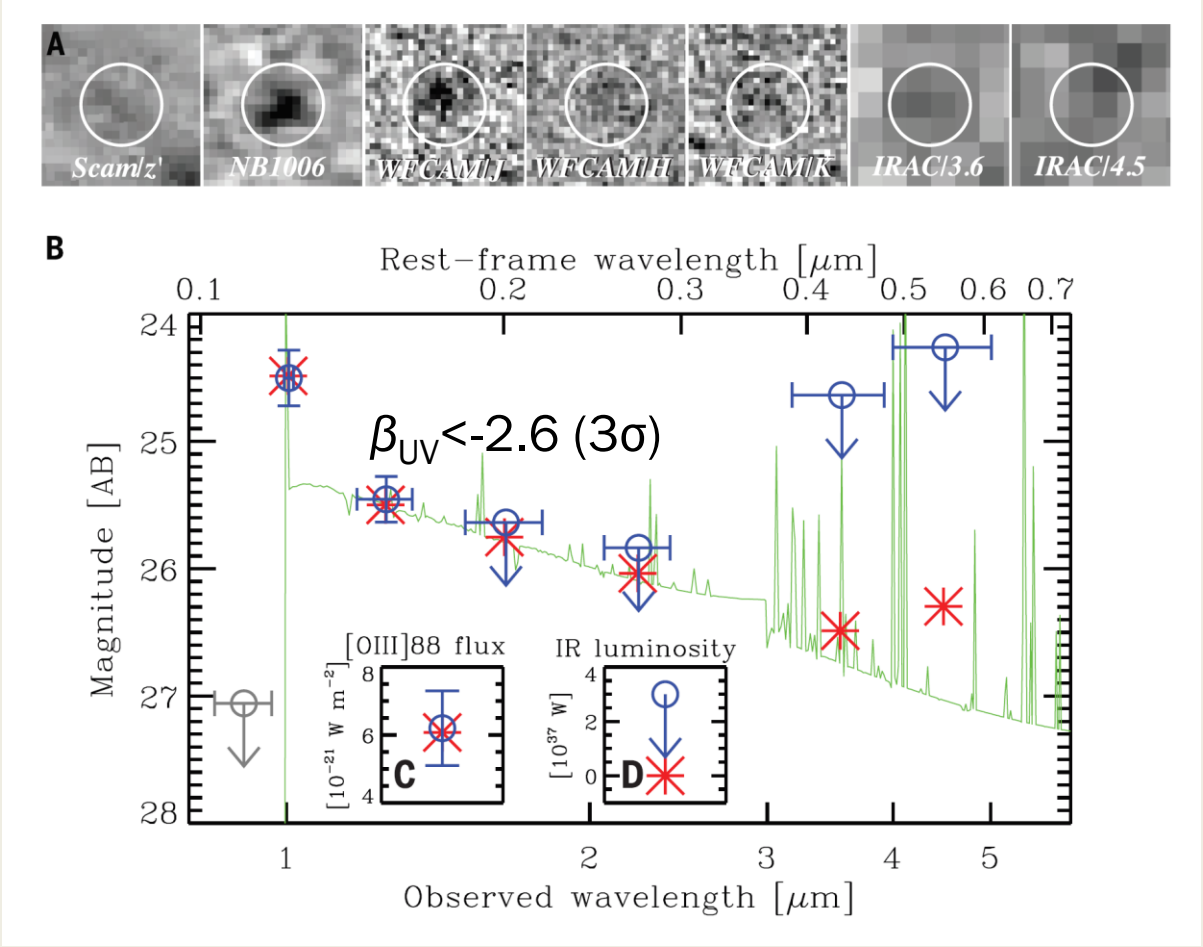
The highest [OIII]/[CII] ever found!

Green: Nearby dwarf galaxies (Cormier+15)
Red: Nearby spiral galaxies (Brauher+08)
Arrows: z~3-4 SMGs (Ferkinhoff+10)

AKInoue+16, Science

SXDF-NB1006-2

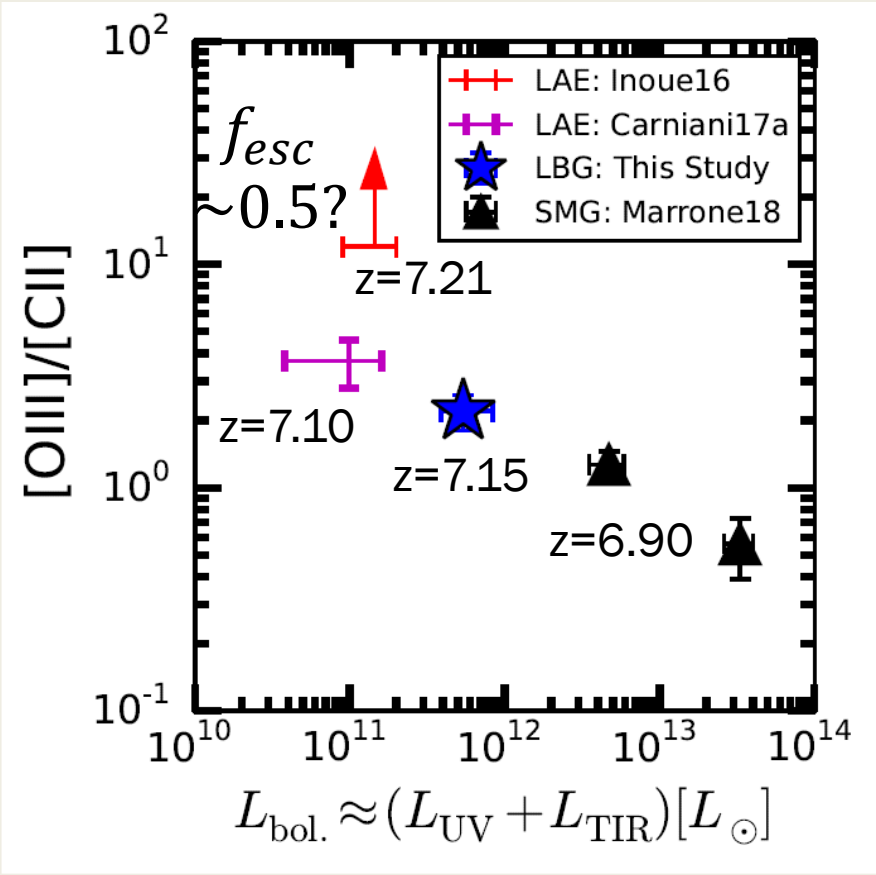
- SED fit with [OIII] line flux and IR upper limit
  - *Escape fraction ~ 0.5 !?*



Hashimoto+AKI+18b

[OIII]/[CII] ratios in the EoR

- LAEs show a higher [OIII]/[CII].
  - *Fainter, less dusty (i.e. less massive?) galaxies are higher in [OIII]/[CII].*

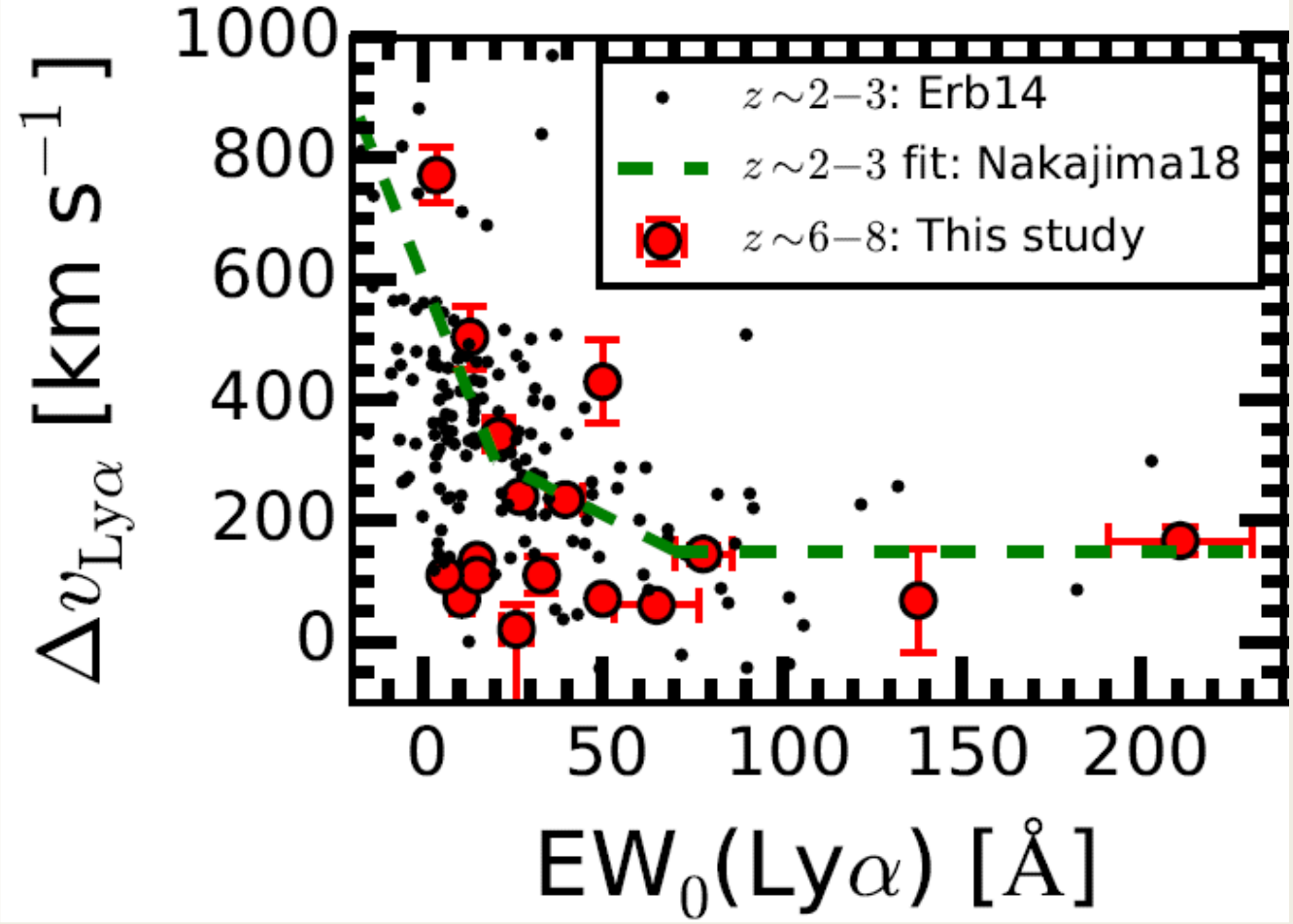


A few z=8-9 objects will be added in a year.

Hashimoto+AKI+18b

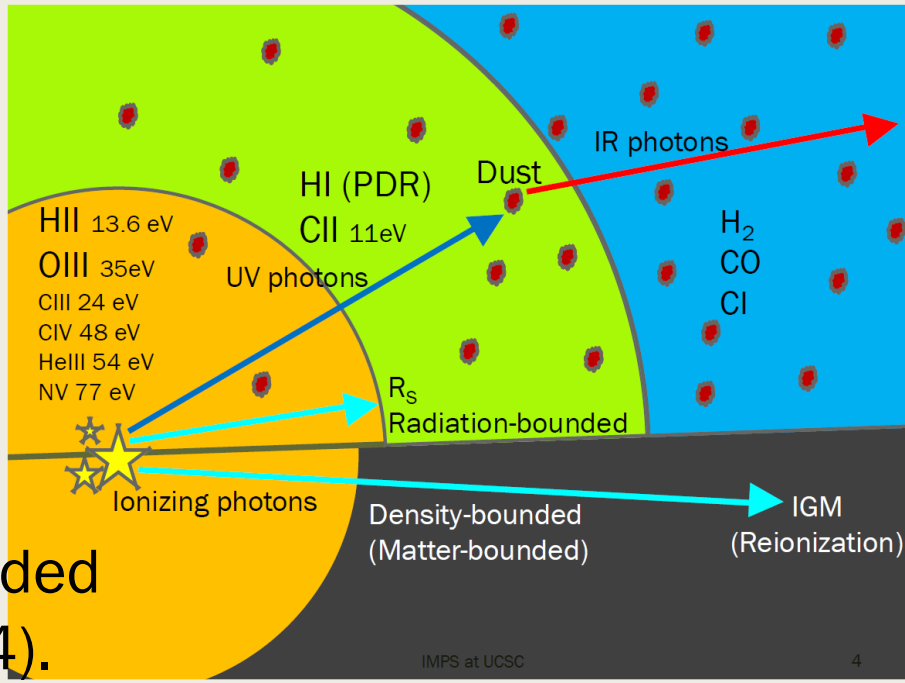
EW(Lyα)-Δv(Lyα) anti-correlation

- A large Lyα velocity offset → a high N_HI
  - *LAEs have a smaller Δv(Lyα) → less HI*



LAE-High [OIII]/[CII]-Cosmic Ionizer?

- LAEs
  - *Large EW(Lyα) → less HI*
  - *Small Δv(Lyα) → less HI*
  - *Weak [CII] → less HI*
  - *Density-bounded?*
  - *High escape of ionizing photons?*



c.f. LAEs at z~2-3 show a higher [OIII]/[OII], implying density-bounded nebulae (Nakajima & Ouchi 2014).

How to verify this?

- SOFIA proposal: PI: T. Hashimoto
  - *Two confirmed LyC leakers at z~0.05*
    - Mrk 54 & Tol 1247
  - *[OIII] 88 micron and [CII] 158 micron*