# Review on high-z galaxy studies with ALMA

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(OSU/NAOJ)

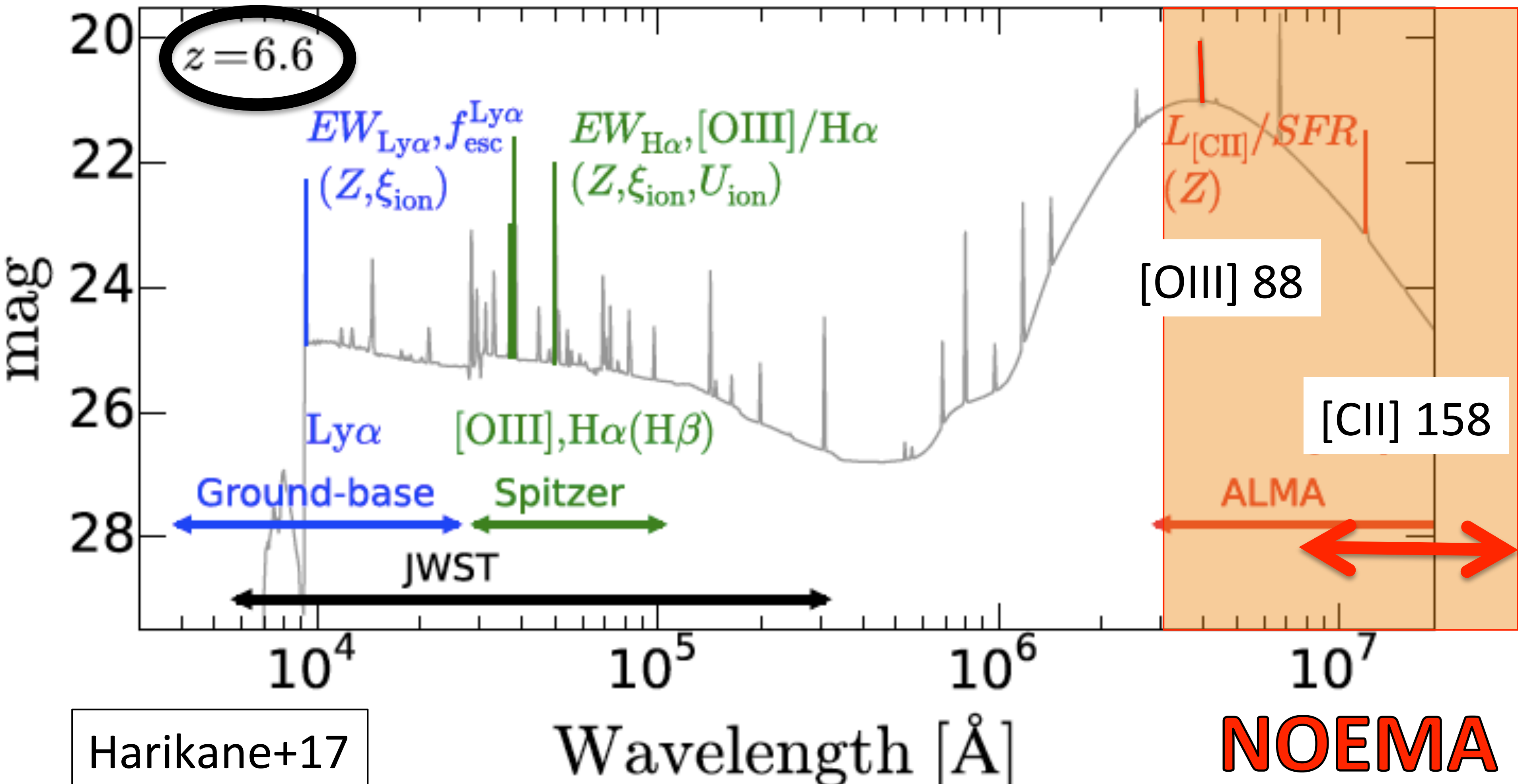
# Contents

- Far-Infrared (FIR) line studies at $z > 5$
  - e.g. [CII] 158 μm and [OIII] 88 μm
  - ISM properteis
  - kinematics
  - morphology

- Dust properteis of galaxies at $z > 5$
  - IRX-β relation

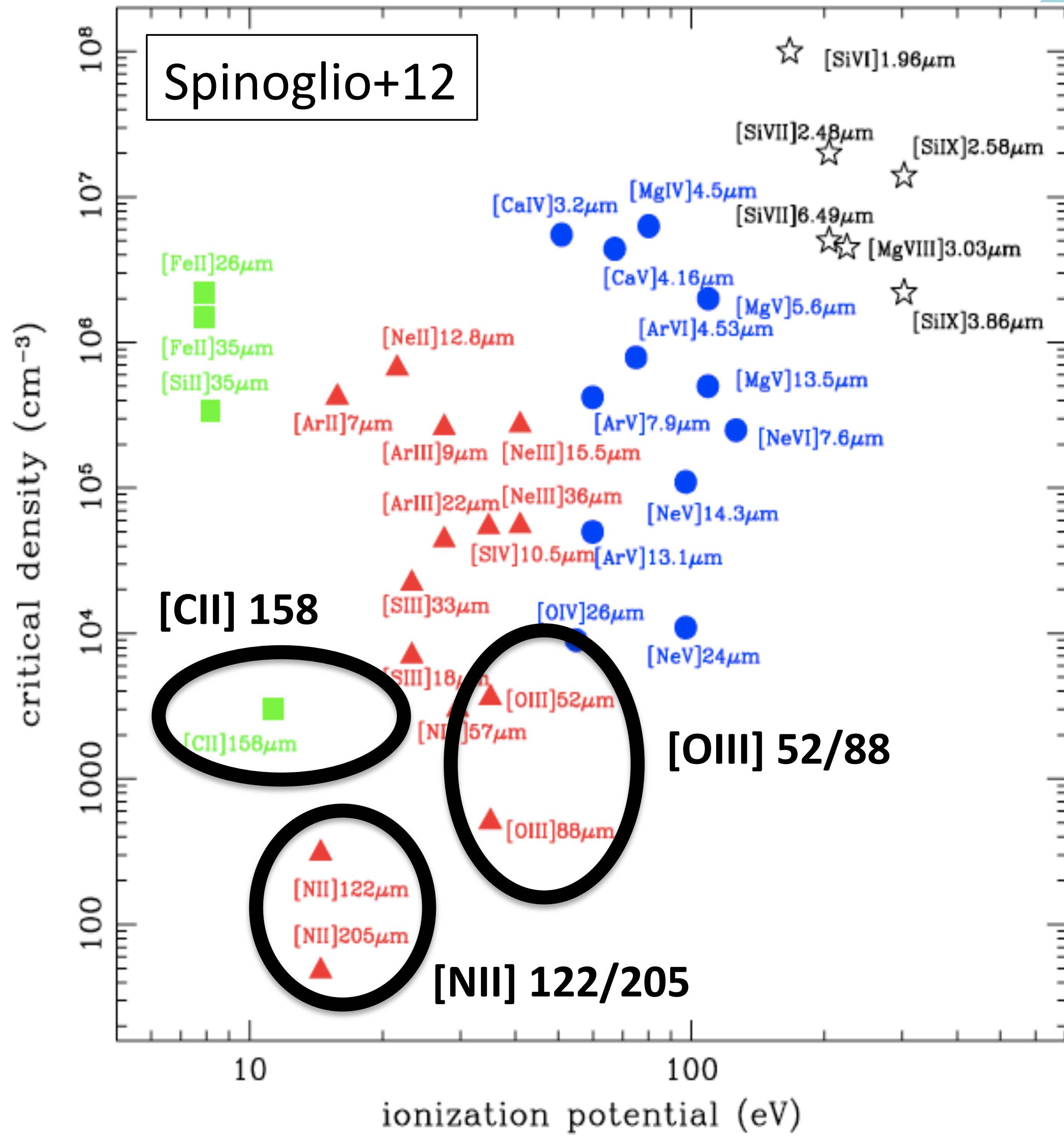
# Reionization studies at mm/sub-mm

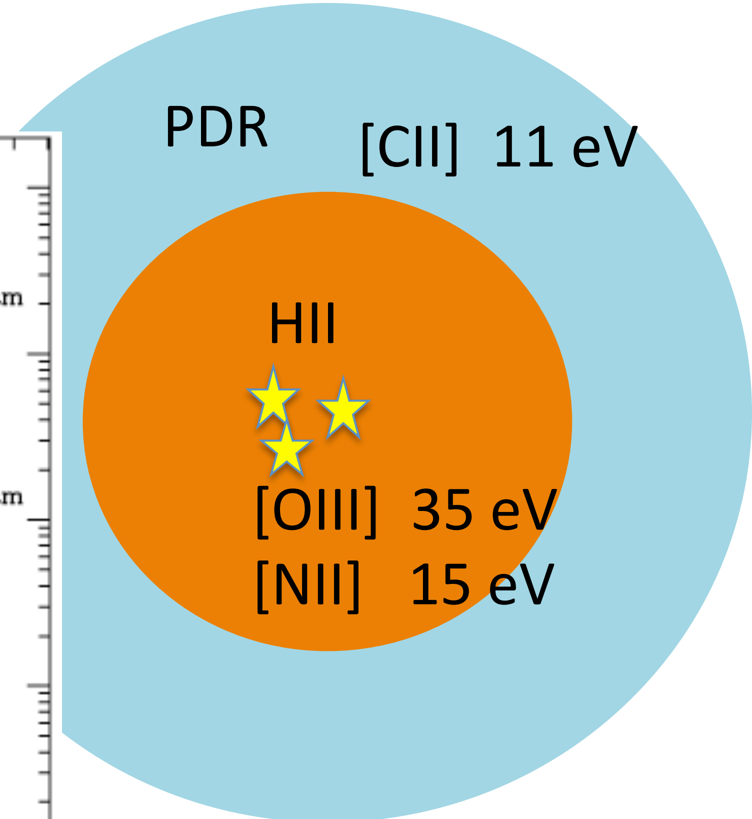
- FIR lines (<u>[CII] 158 μm and [OIII] 88 μm</u>) are useful
- <u>Dust continuum</u> can be simultaneously targeted




Harikane+17

# FIR lines

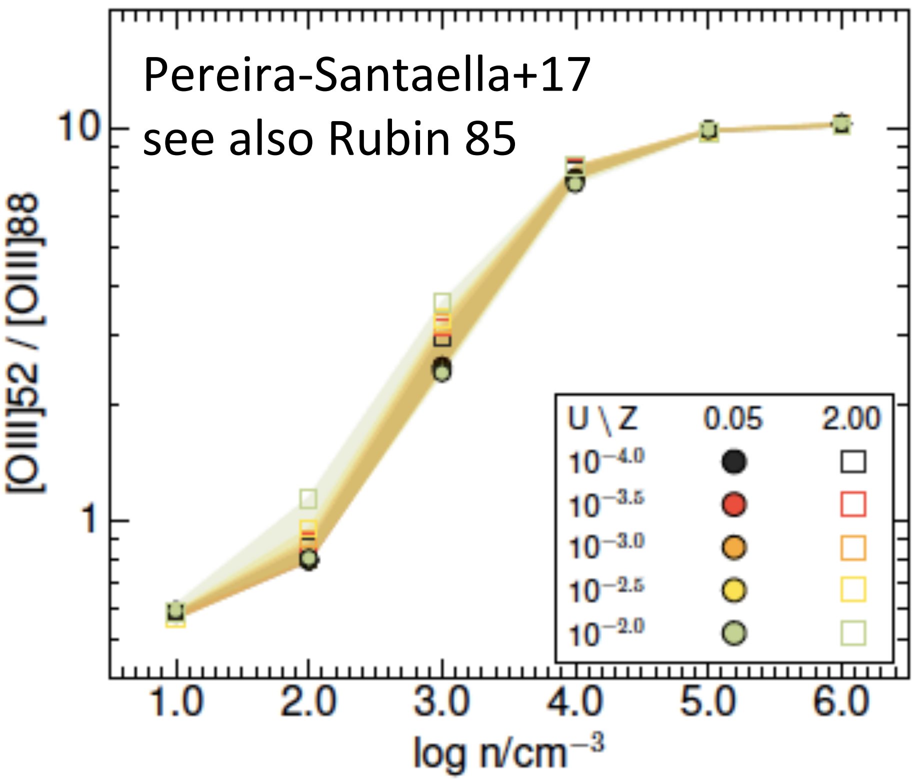


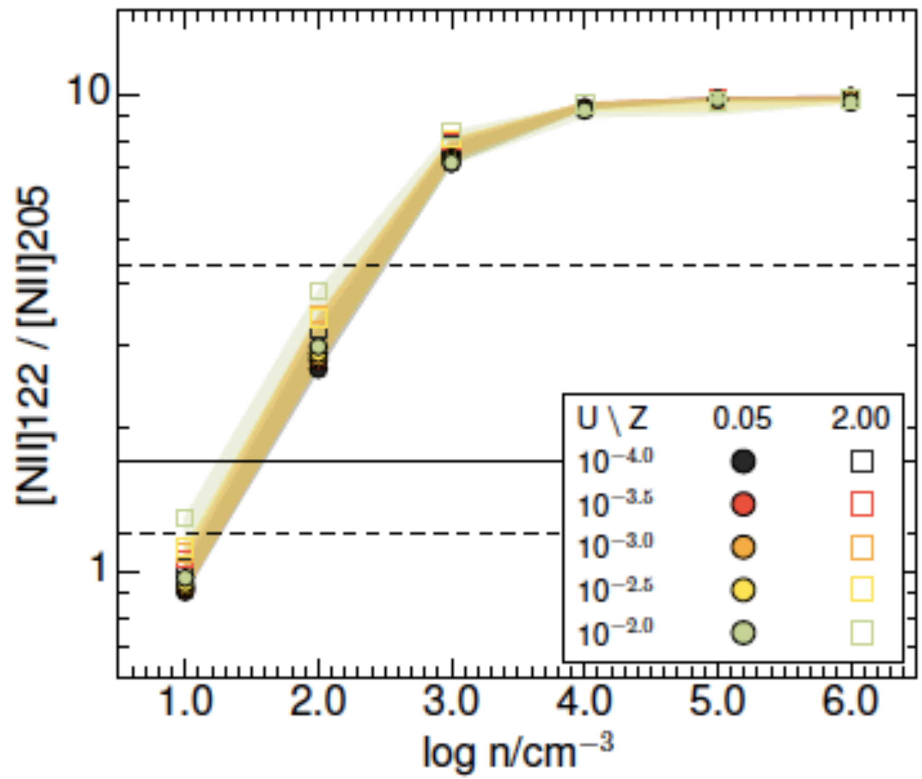

| Line | $n_{crit}$ [$cm^{-3}$] | $P_{ion}$ [eV] |
|---|---|---|
| [CII] 158 | ~3000 | 11 |
| [OIII] 52 | ~4000 | 35 |
| [OIII] 88 | ~500 | 35 |
| [NII] 122 | ~400 | 15 |
| [NII] 205 | ~50 | 15 |

# Electron density

### [OIII] 52/ [OIII] 88



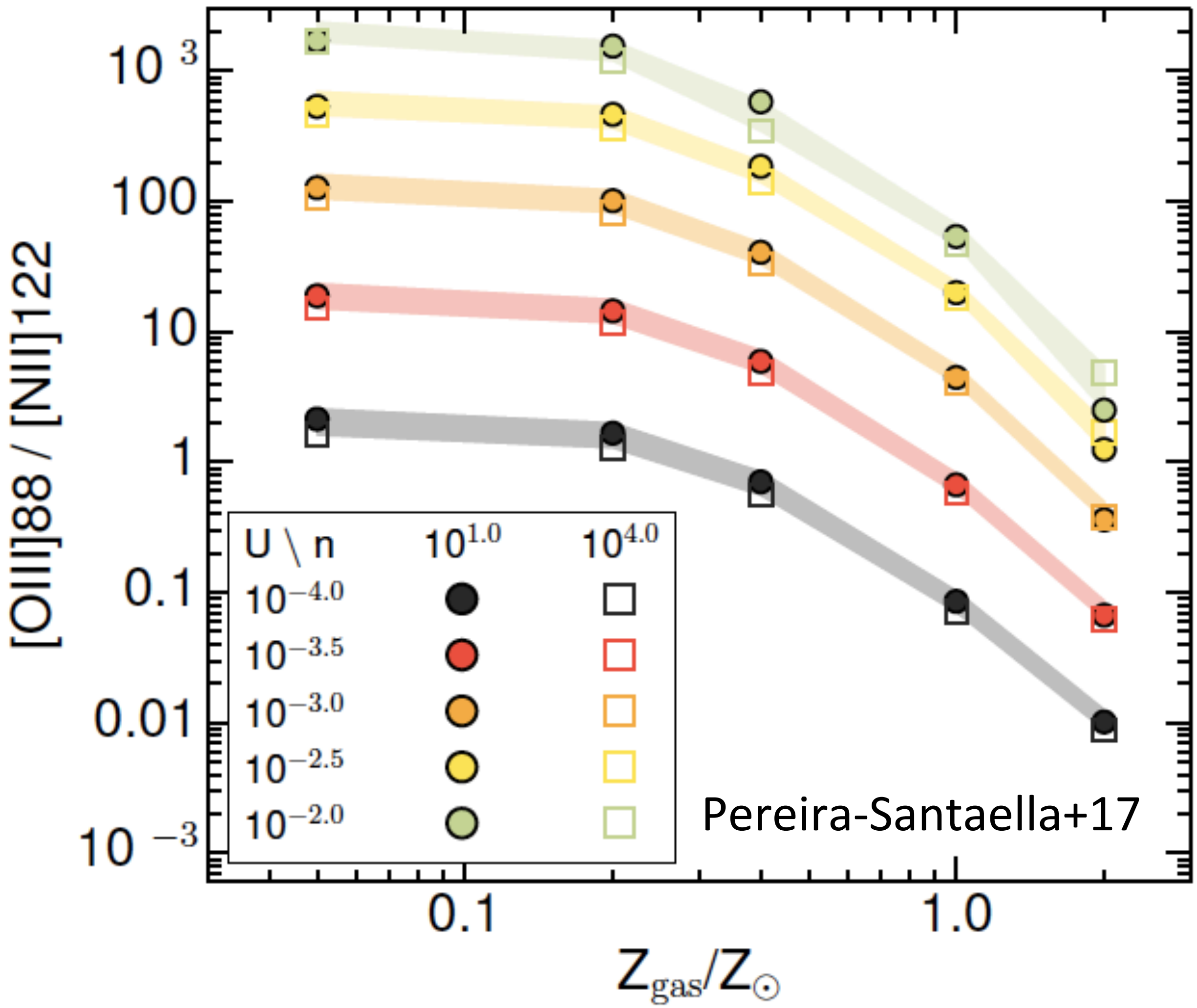

### [NII] 122/ [NII] 205




-CLOUDY (HII region alone)
-STARBURST99

log U = -4.0, -3.5, ..., -2.0 (in spteps of 0.5 dex)
Z/Zo = 0.05,  0.2, 0.4, 1.0, 2.0

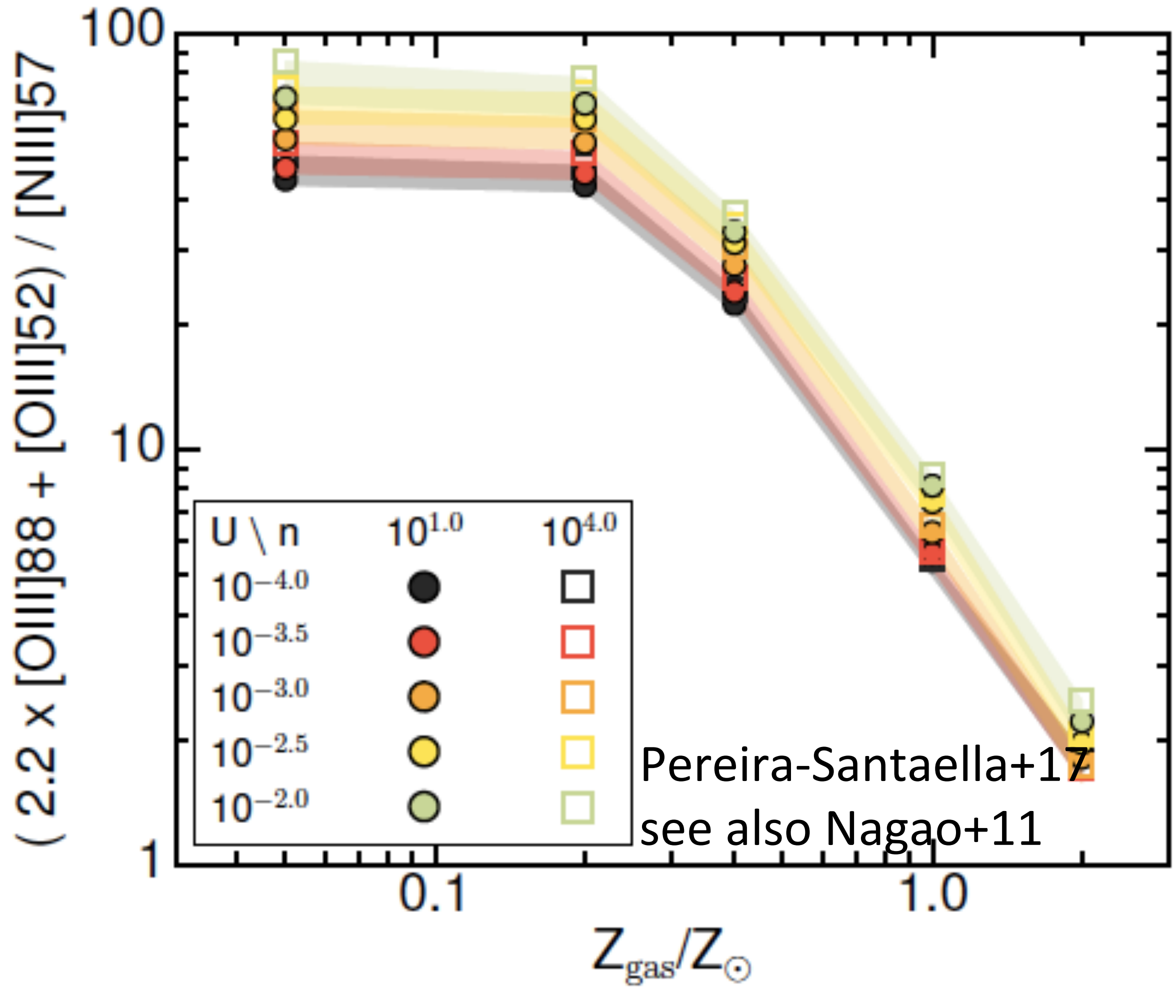
# Ionization parameter




[OIII] 88 and [NII] 122 have similar $n_{crit}$.

[OIII]88/[NII]122 can be used to estimate U if a rough estimate of Z is available.

# Metallicity

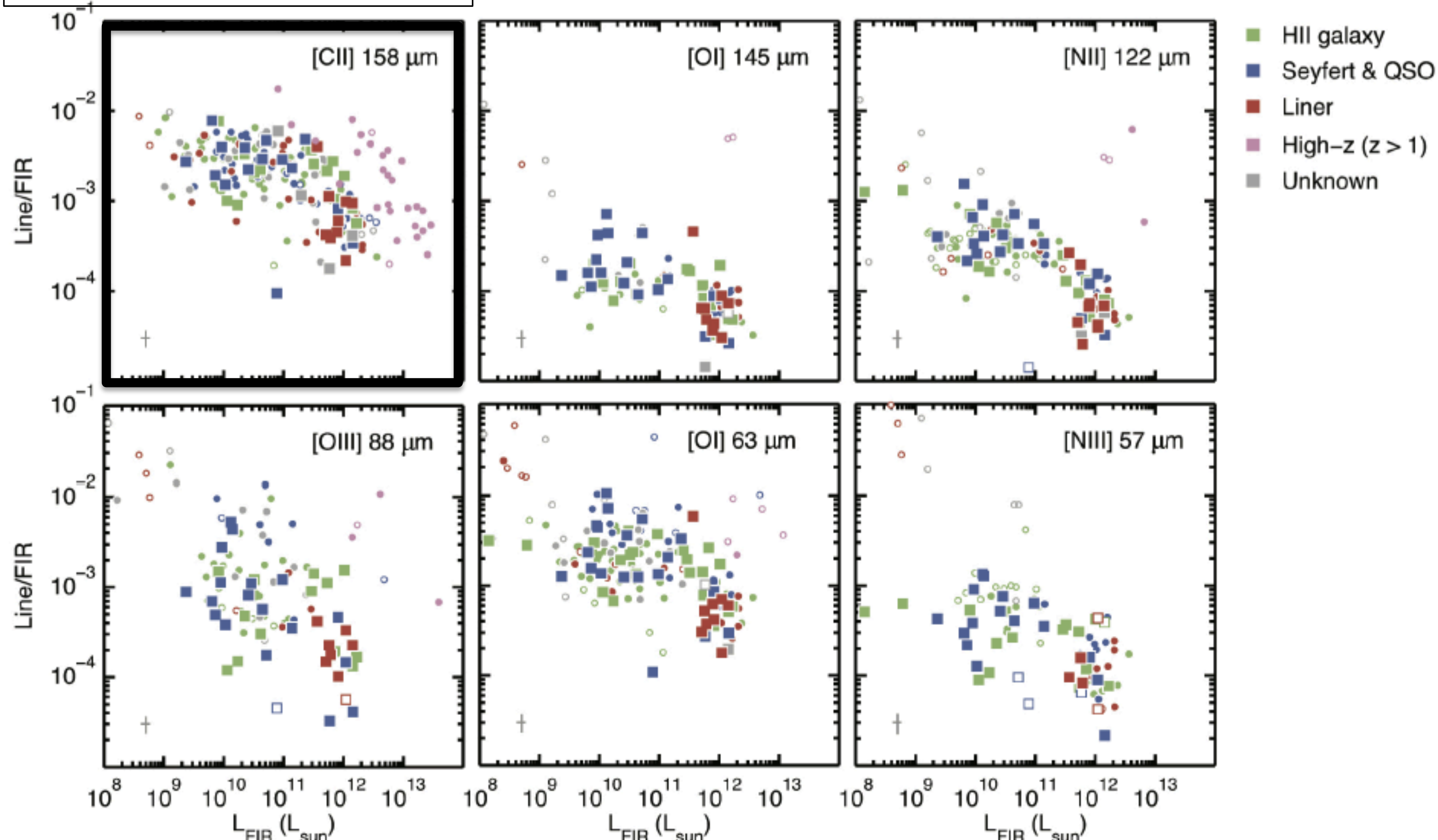



- FIR lines → n, U, Z with less dust effects
- FIR lines → now accessible with ALMA

# [CII] 158μm as a traditional tool at high-z

- [CII] is the strongest FIR line in **local spiral** galaxies (e.g. Brauher+08)

Herrera-Camus+18a,b SHINING survey (Hershcel/PACS): 52 objects

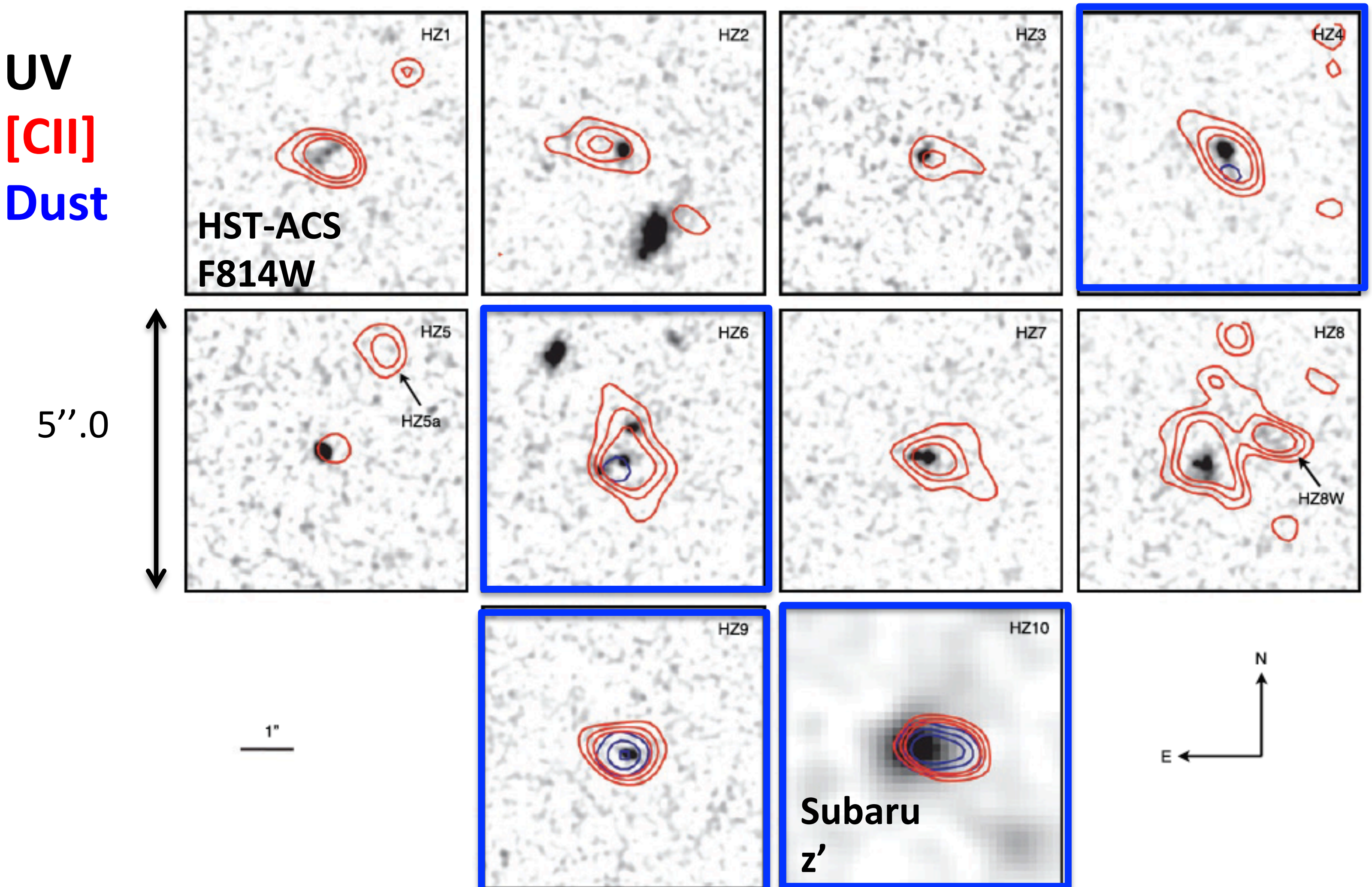


# [CII] 158μm as a traditional tool at high-z

- 21 [CII] detections at z > 5 (e.g Capak+15, Carniani+17, Smit+18)

Capak+15, *Nature*

9 galaxies with ~ 1-4 $L_*$ & 1 quasar at z = 5.2 – 5.7



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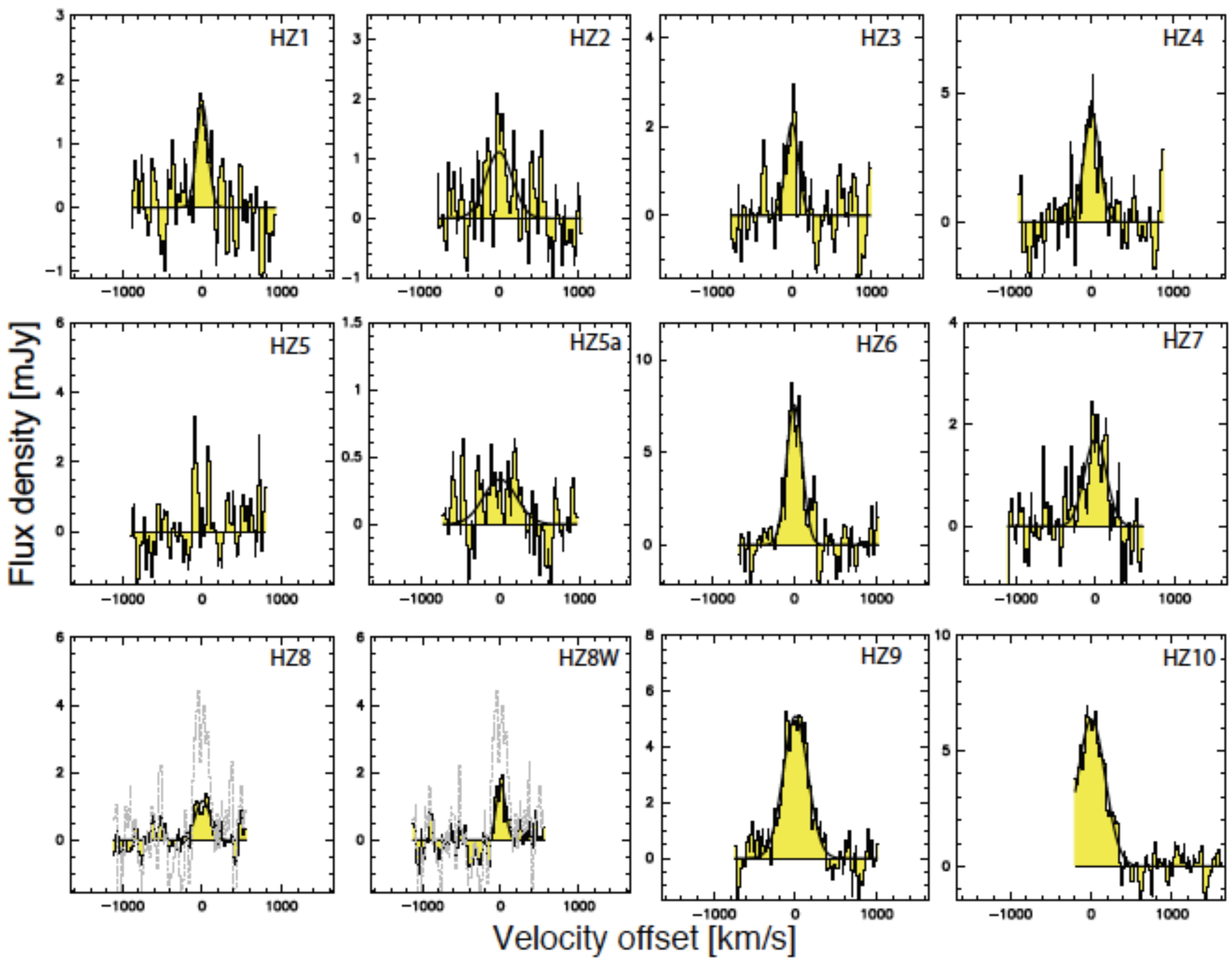
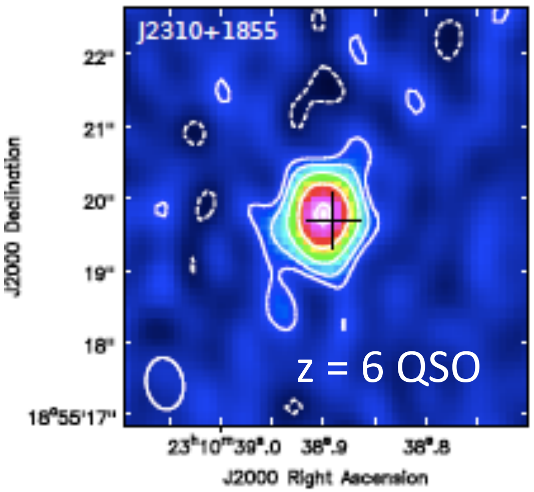
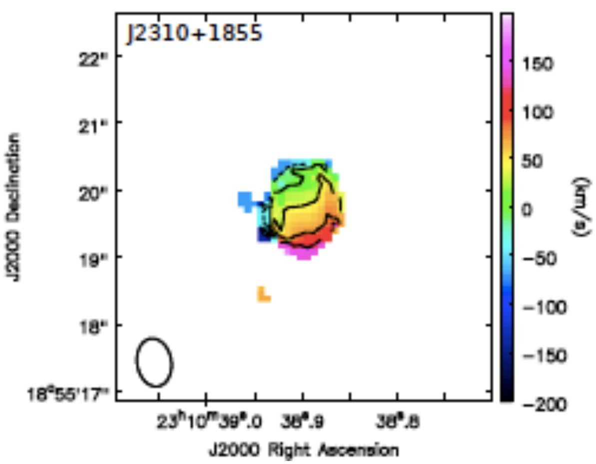


# Dynamical mass taced by [CII]

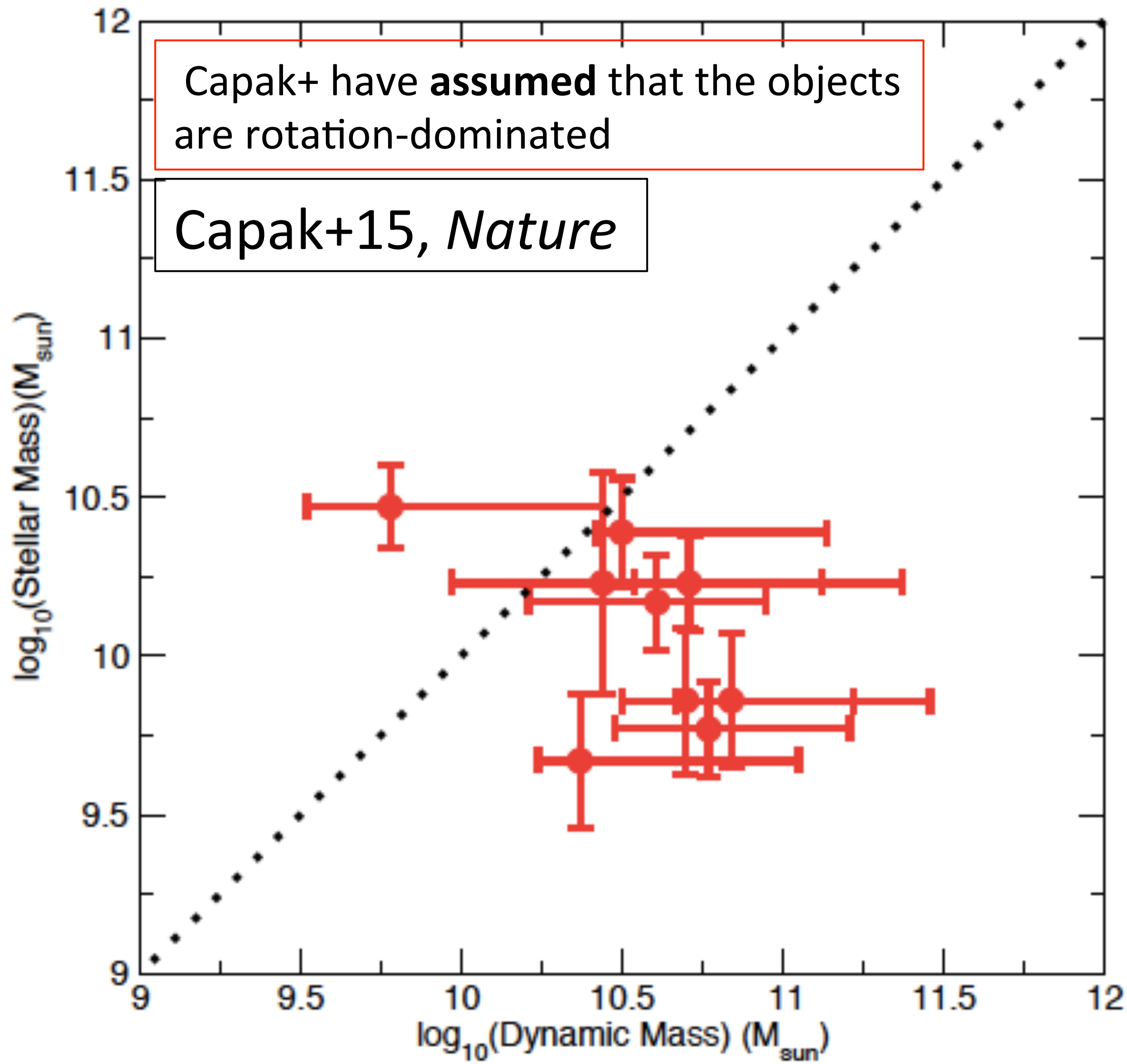
R. Wang+13




Capak+ have **assumed** that the objects are rotation-dominated

Capak+15, *Nature*



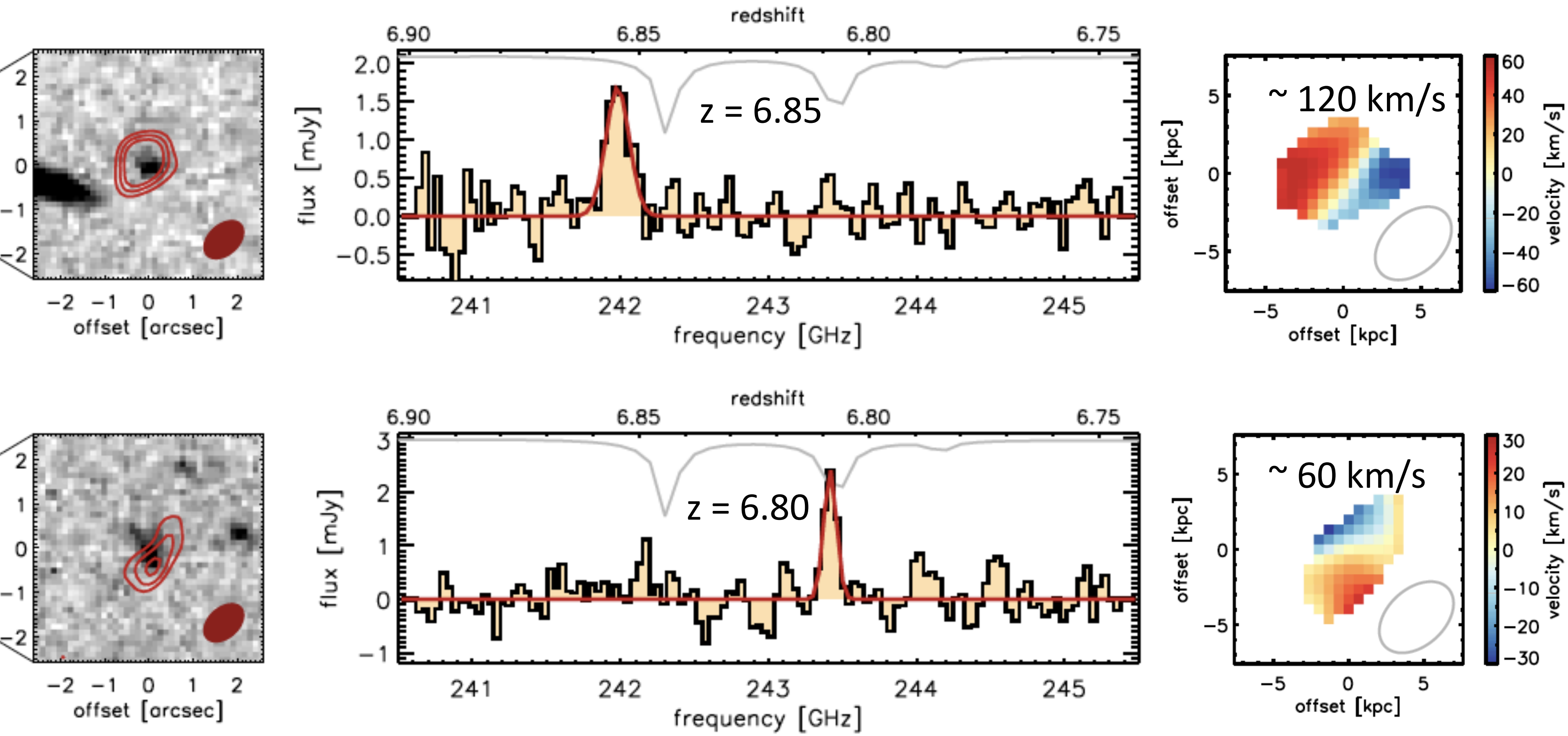

$$M_{\rm dyn} = G^{-1}\, R_{\rm [CII]}\, (0.75\, {\rm FWHM}/\sin i)^2$$

see also Bradac+16, Matthee+17, Izumi+18

# [CII] 158μm as a kinematical tool

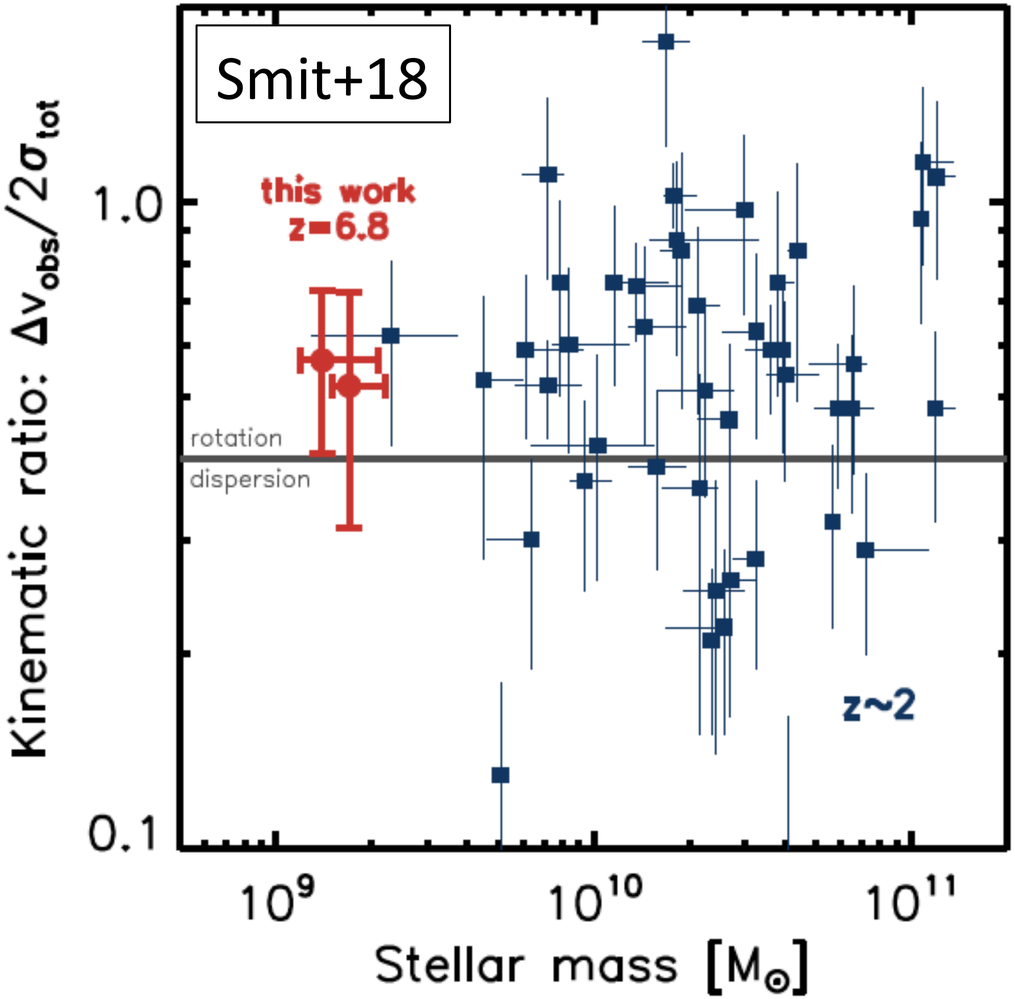
Smit+18, *Nature*

2 galaxies with $L_{UV}$ ~ 1-2 $L_*$ and SFRs ~ 20 Msun/yr




- [CII] detections without *a priori* $z_{spec}$
- No dust continuum
- [CII] velocity gradients ➔ rotation (next page)

# [CII] 158µm as a kinematical tool

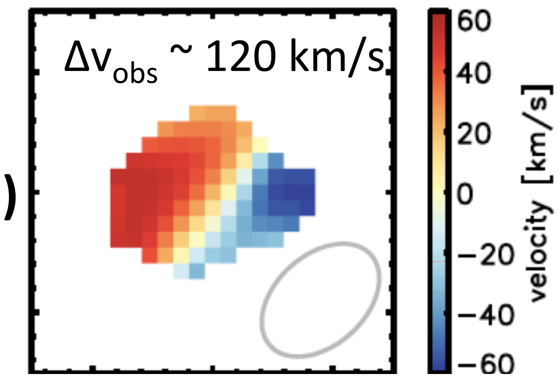



**z ~ 2 Hα emitters (SINS survey)**
**Forster-Schreiber+09**

***rotation***

**0.4 (empirical)**

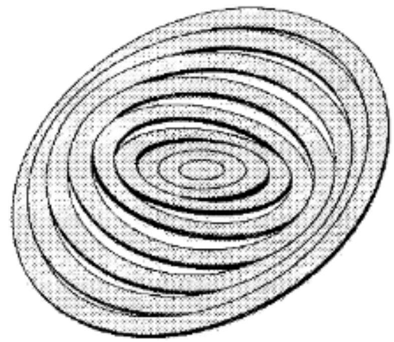
***dispersion***



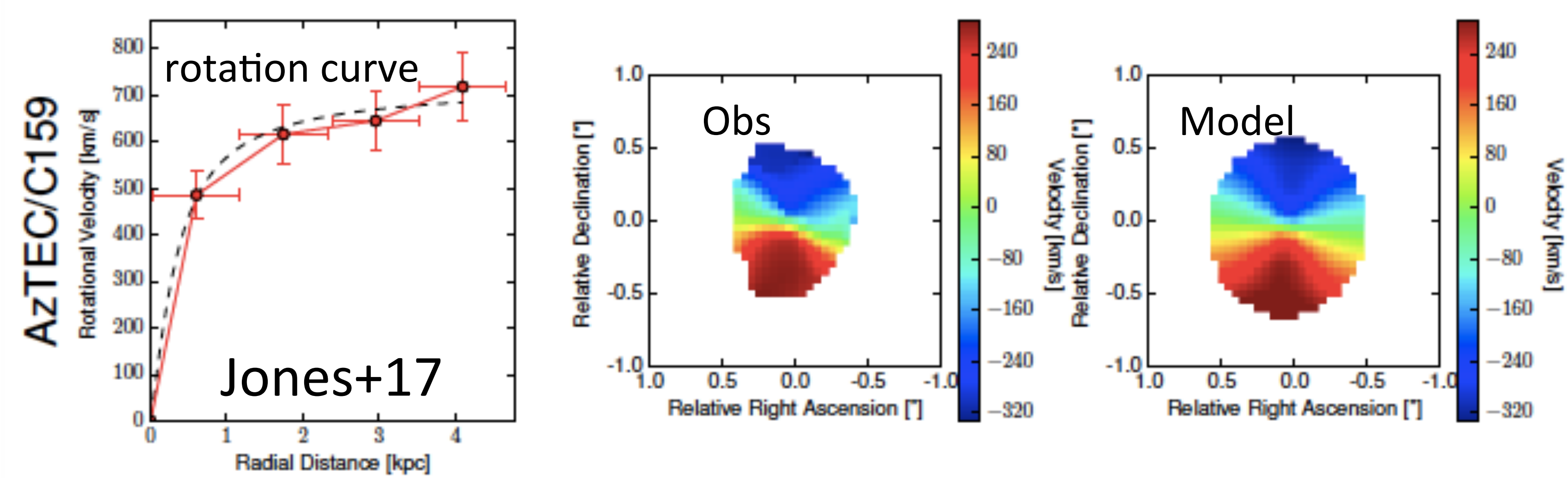

If velocity radients are due to rotation, the two galaxies are expected to be similar in dynamical properties to the rotation-dominated disks seen for massive galaxies at z ~ 2.

# [CII] 158µm as a kinematical tool

There are some attempts at high-z to model the velocity field with the ``tilted-ring model'' (e.g. van der Hulst+1992: GIPSY model)



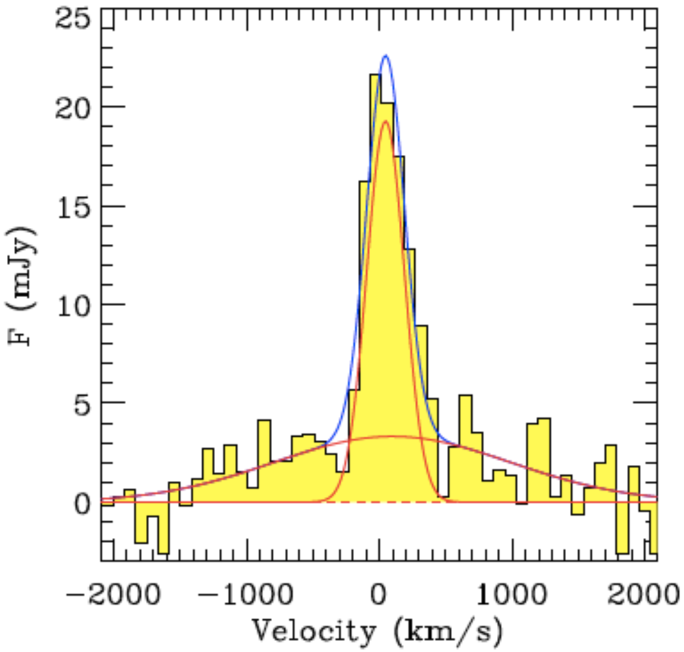
- -Ring number
- -Ring width
- -Position angle
- -Inclination
- -Velocity



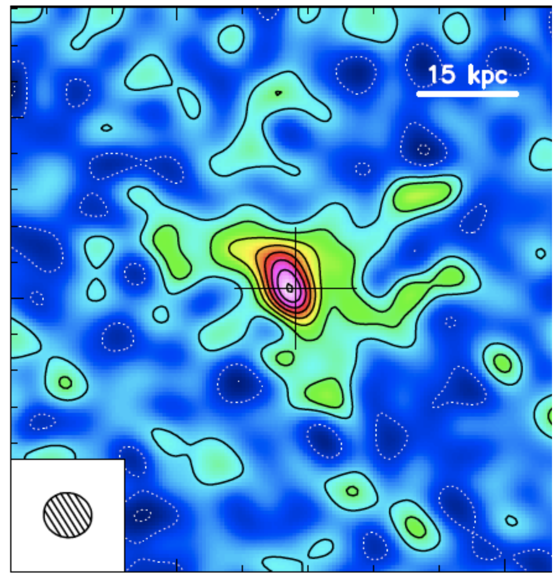

- Model fit for 2 LBGs, 1 DLA, 2 SMGs, 1 QSO at z = 4 - 6
- E.g., AzTEC/C159 show a flat curve → rotation → accurate $M_{dyn}$
- High S/N (> 15) data with fine angular resolutions are required

# Outflow traced by [CII]

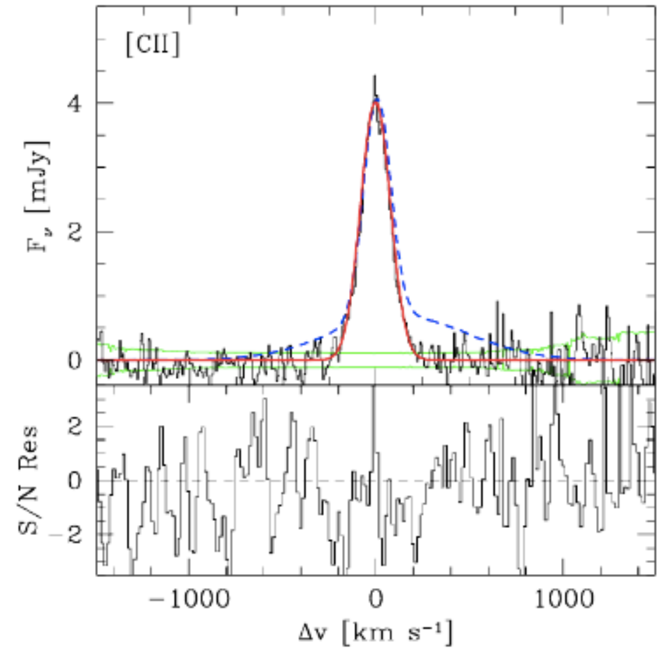
Maiolino+12 PdBI




Cicone+15 PdBI




Decarli+18 ALMA stack

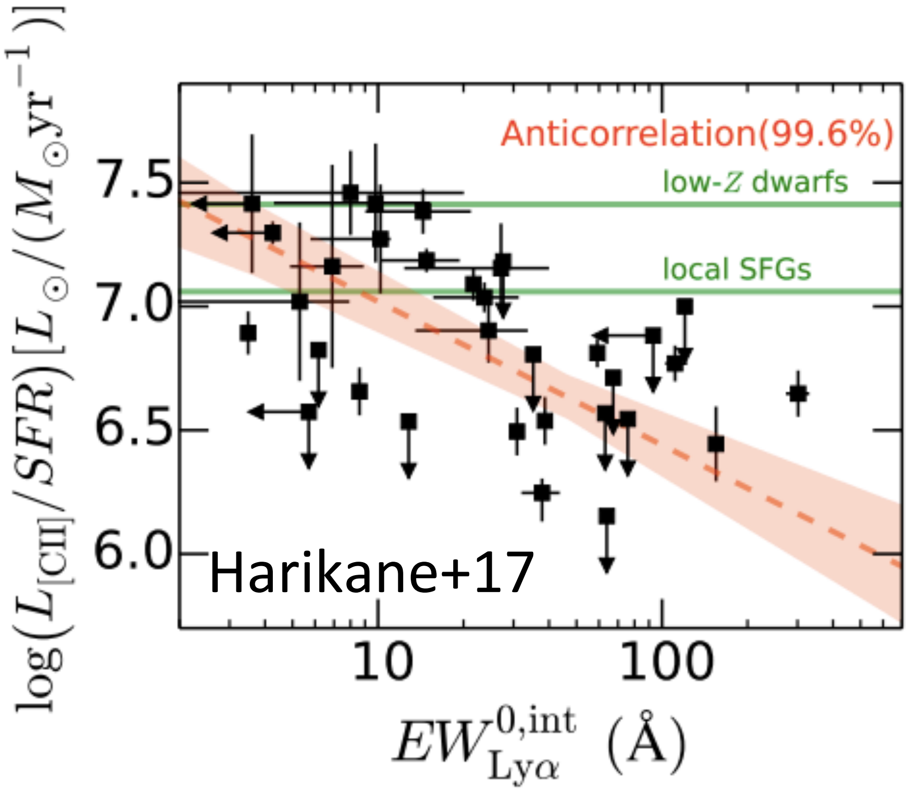


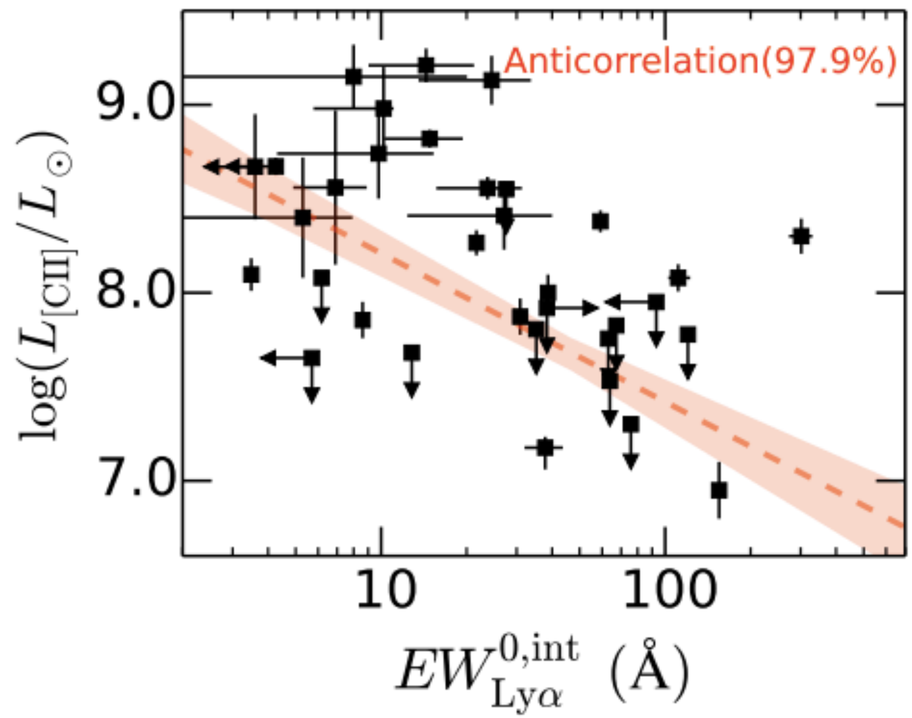

A QSO at z = 6.42 (J1148+5251) has

- a broad line component with FWHM ~ 2000 km/s
- a very extended morphology with FWHM ~ 17 kpc (r ~ 30 kpc)
- an outflow rate > 3500 Msun/yr

However, a stacked spectrum of <u>27 QSOs</u> obtained with ALMA
do not show extended compoenent → J1148+5251 is a unique object

# Is [CII] 158μm a good target ?

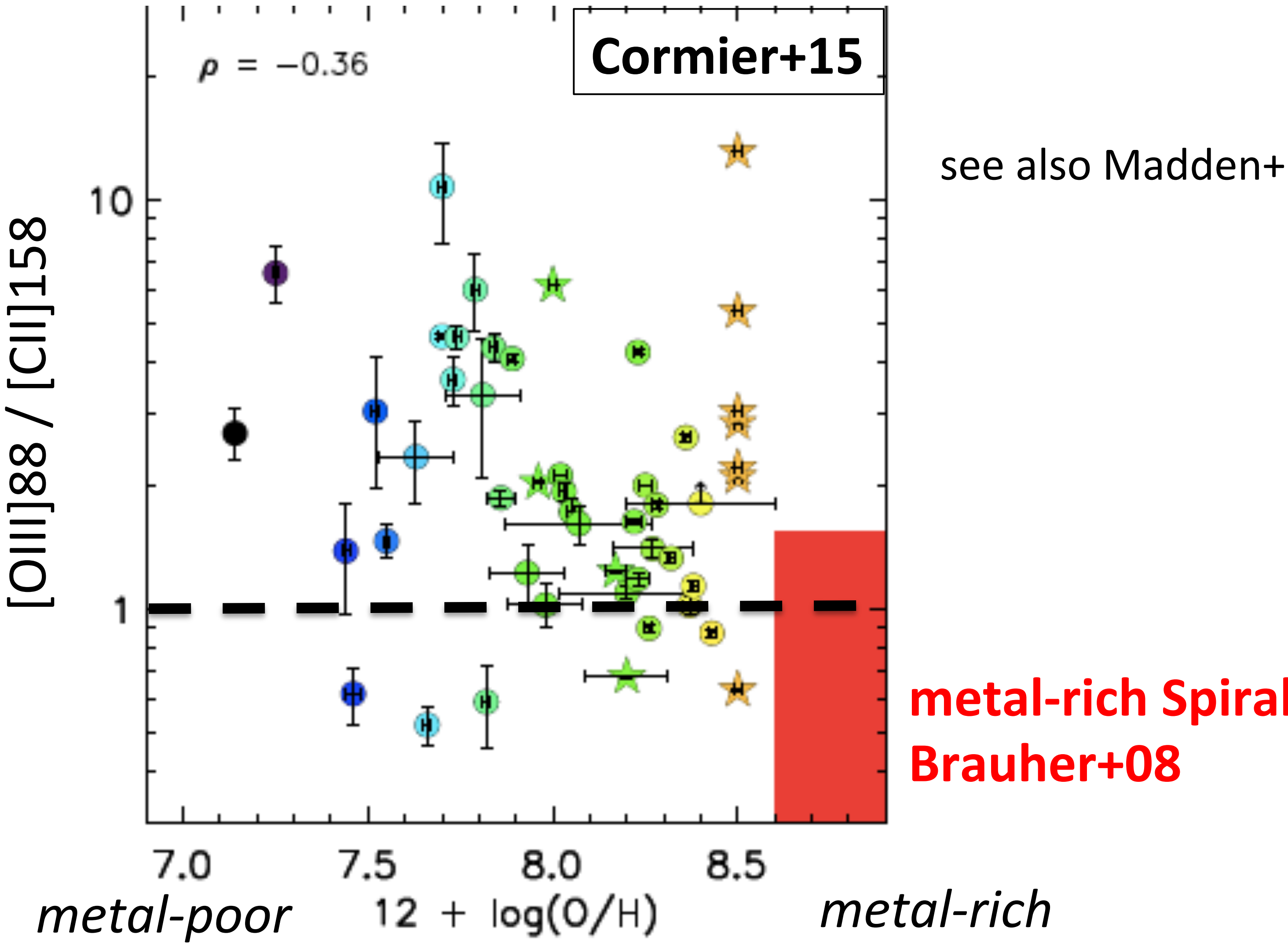



- Mixing results of detections and null-detections
- LAEs show weak [CII] 158 (e.g, Ouchi+13, Ota+14, Inoue+16)
- Low metallicity and/or high ionization parameter of LAEs lead to weak [CII] (see also Carniani+18b)

# [OIII] 88 µm as a ``new'' tool at high-z

✓ [OIII] > [CII] for **local dwarf** galaxies




see also Madden+12

# [OIII] 88 μm as a ``new'' tool at high-z

Cormier+15

Herschel/PACS Dwarf Galaxy Survey: 45 low-Z galaxies

| | Full DGS sample | B08 sample |
|---|---|---|
| *PACS line ratio* | | |
| [O I]$_{63}$/[C II]$_{157}$ . . . . . . . . . . . . . . . . . | $0.59^{3.31}_{0.27}$ (0.15 dex) | 0.72 (0.25 dex) |
| [O III]$_{88}$/[C II]$_{157}$ . . . . . . . . . . . . . . . . | $2.00^{13.0}_{0.52}$ (0.34 dex) | 0.54 (0.45 dex) |
| [O I]$_{145}$/[O I]$_{63}$ . . . . . . . . . . . . . . . . . | $0.074^{0.17}_{0.041}$ (0.06 dex) | 0.063 (0.25 dex) |
| [O III]$_{88}$/[O I]$_{63}$ . . . . . . . . . . . . . . . . . | $2.96^{11.8}_{0.99}$ (0.24 dex) | 0.74 (0.25 dex) |
| [O III]$_{88}$/[N II]$_{122}$ . . . . . . . . . . . . . . . . | $86.3^{442}_{26.7}$ (0.23 dex) | 3.27 (0.37 dex) |
| [N III]$_{57}$/[N II]$_{122}$ . . . . . . . . . . . . . . . . | $8.06^{9.86}_{5.75}$ (0.13 dex) | 1.91 (0.57 dex) |
| [N II]$_{122}$/[C II]$_{157}$ . . . . . . . . . . . . . . . | $0.025^{0.054}_{0.015}$ (0.23 dex) | 0.12 (0.21 dex) |
| [N III]$_{57}$/[O III]$_{88}$ . . . . . . . . . . . . . . . . | $0.17^{0.29}_{0.067}$ (0.52 dex) | 1.08 (0.44 dex) |
| [N II]$_{205}$/[N II]$_{122}$ . . . . . . . . . . . . . . . | < 1 | – |

# [OIII] 88 μm as a ``new'' tool at high-z

ALMA WILL DETERMINE THE SPECTROSCOPIC REDSHIFT $z > 8$ WITH FIR [O III] EMISSION LINES

A. K. INOUE[1], I. SHIMIZU[1,2], Y. TAMURA[3], H. MATSUO[4], T. OKAMOTO[5], AND N. YOSHIDA[6,7]

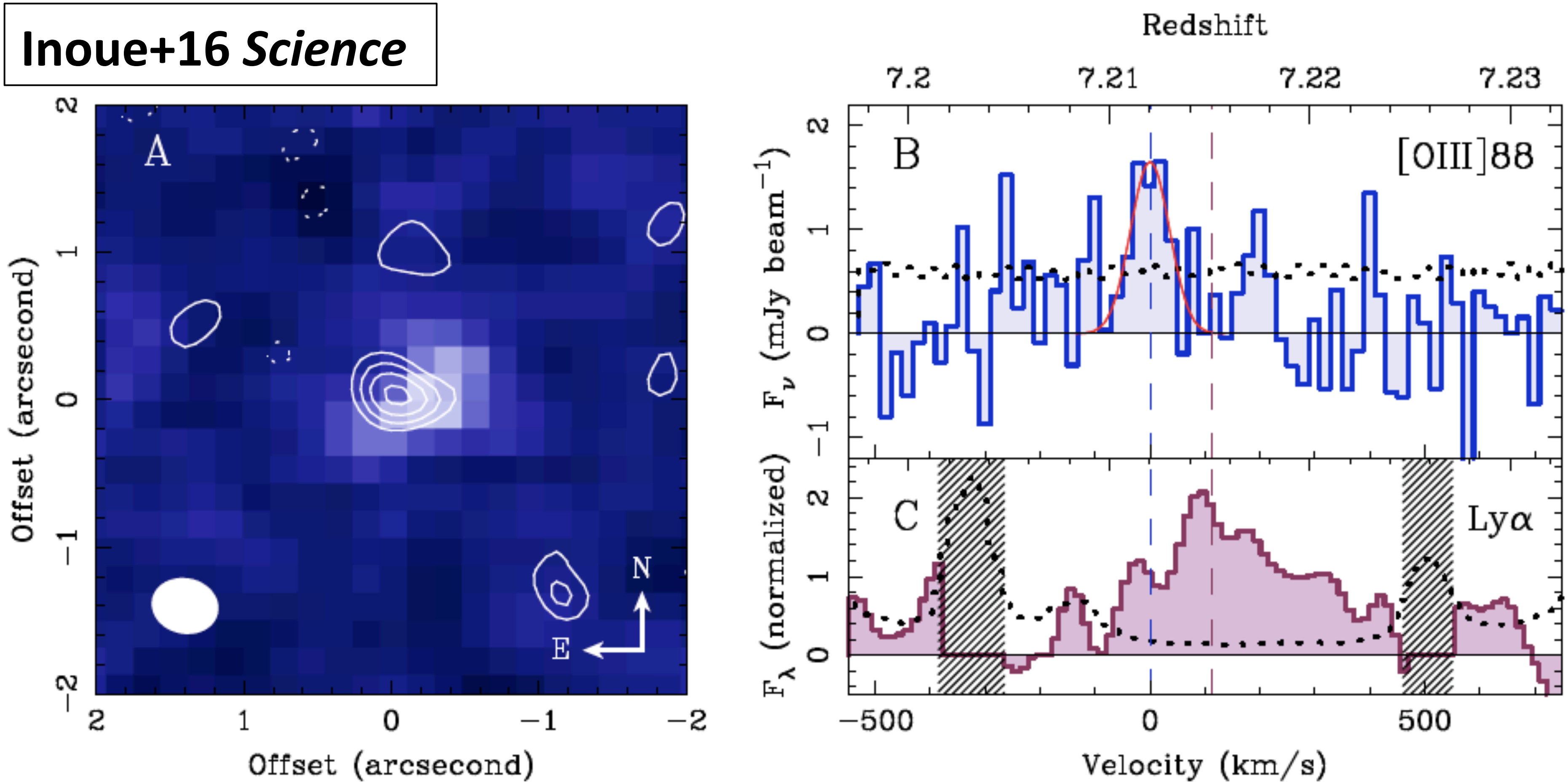
ABSTRACT

We investigate the potential use of nebular emission lines in the rest-frame far-infrared (FIR) for determining spectroscopic redshift of $z > 8$ galaxies with the Atacama Large Millimeter/submillimeter Array (ALMA). After making a line emissivity model as a function of metallicity, especially for the [O III] 88 $\mu$m line which is likely to be the strongest FIR line from H II regions, we predict the line fluxes from high-$z$ galaxies based on a cosmological hydrodynamics simulation of galaxy formation. Since the metallicity of galaxies reaches at $\sim 0.2\ Z_{\odot}$ even at $z > 8$ in our simulation, we expect the [O III] 88 $\mu$m line as strong as 1.3 mJy for 27 AB objects, which is detectable at a high significance by <1 hr integration with ALMA. Therefore, the [O III] 88 $\mu$m line would be the best tool to confirm the spectroscopic redshifts beyond $z = 8$.

- Coslomogical simulations of Shimizu+13
- CLOUDY calculations for HII regions

# The first detection of [OIII] 88 μm in the EoR (Epoch of the Reionization) at z = 7.21

Inoue+16 *Science*

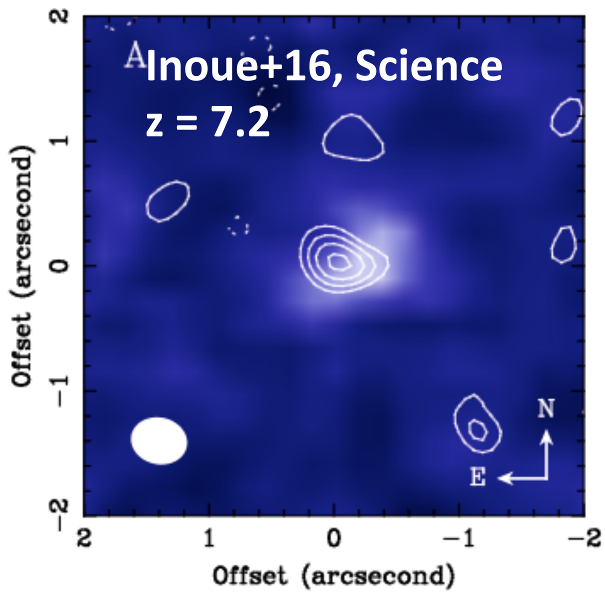


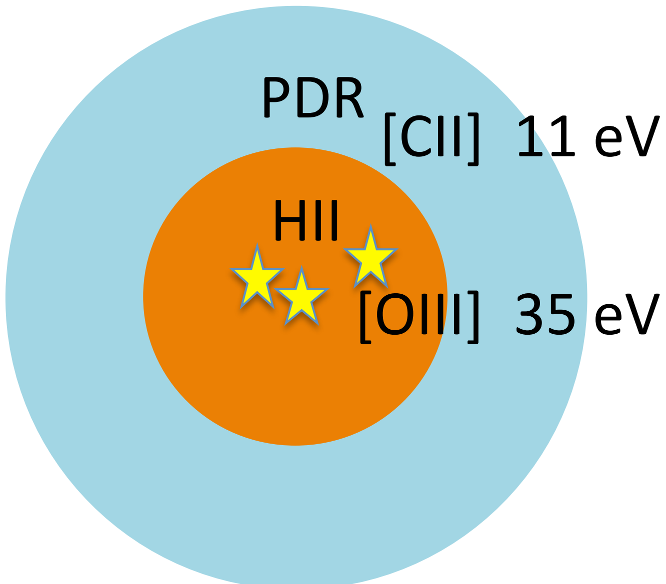

ALMA [OIII] contour
on Subaru Lyα image (Shibuya+12)

Δv(Lyα) = +110 km/s
➔ low $N_{HI}$ (cf., Verhamme+06)

# The first detection of [OIII] 88 μm in the EoR (Epoch of the Reionization) at z = 7.21

- [CII] is not detected (Inoue+16)




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

<u>**Unusually low neutral gas in the ISM → High LyC escape ?**</u>

**Two years have passed, and…**

# 10 objects with [OIII] 88 μm detections !

| Literature | z | population | features |
|---|---|---|---|
| Hashimoto+18a, *Nature* | 9.11 | LBG/LAE | [OIII] 88 |
| Laporte+17 | 8.38 | LBG/LAE | [OIII] 88, dust |
| Tamura incl. Hashimoto+ 18 | 8.31 | LBG | [OIII] 88, dust |
| Inoue+16, *Science* | 7.21 | LAE | [OIII] 88 |
| Hashimoto+18b | 7.15 | LBG/LAE | [OIII] 88, [CII] 158, dust |
| Carniani+17 | 7.10 | LAE | [OIII] 88, [CII] 158 |
| Marrone+18, *Nature* | 6.90 | SMG | [OIII] 88, [CII] 158, dust |
| Hashimoto+18d in prep. | 6.31 | LAE | [OIII] 88, [CII] 158 |
| Sunaga incl. TH+18 in prep | 6.11 | LAE | [OIII] 88 |
| Hashimoto+18c soon. | 6.04 | QSO | [OIII] 88, [CII] 158, dust |

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| Inoue+16, | | | |
| Hashimoto | | | 8, dust |
| Carniani+1 | | | 8 |
| Marrone+18, *Nature* | 6.90 | SMG | [OIII] 88, [CII] 158, dust |
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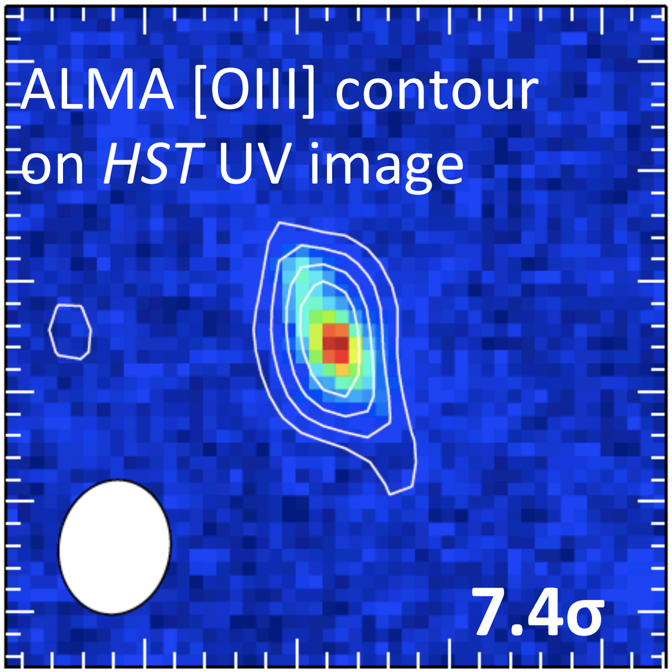
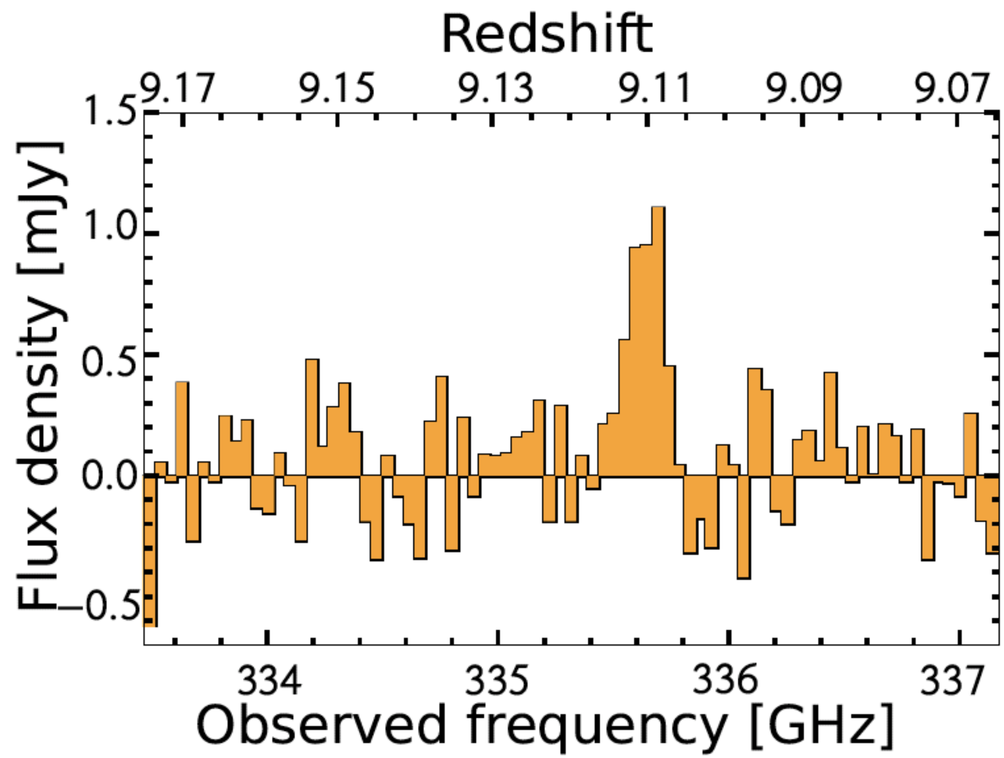
**Success rate is 100 %**
**(7 out of 7)**

# The most distant galaxy with a spectral line: MACS1149-JD1 at z = 9.11

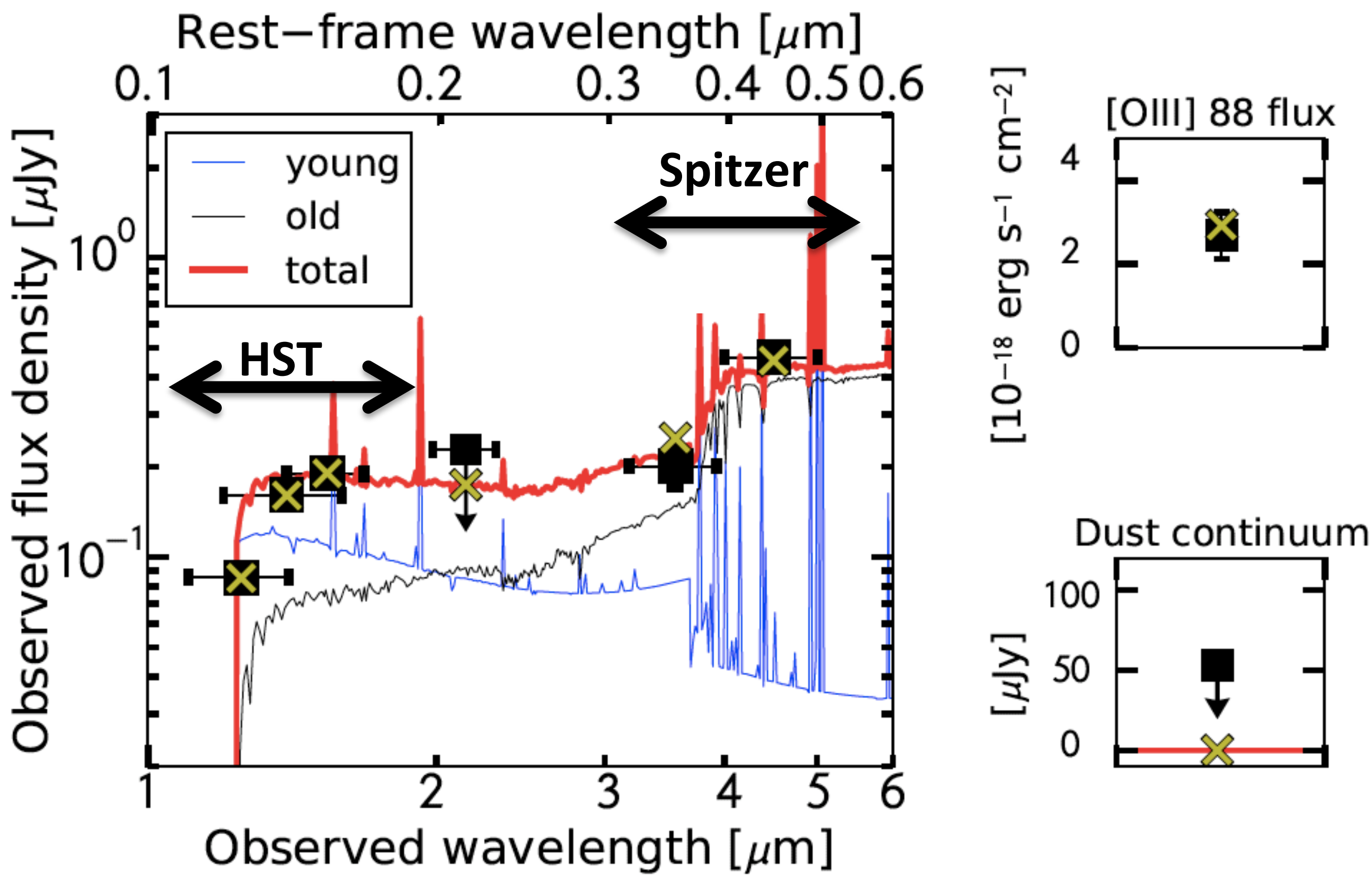
**Hashimoto+18a *Nature***




- ✓ A lensed (μ ~ 10) LBG at z ~ 9.6 (9.0-9.8) (Zheng+12)
- ✓ $T_{obs}$ ~ 5 hrs
- ✓ [OIII] detection without *a priori* spectroscoic redshift information
- ✓ [OIII] is established as a powerful tool for identifying z > 7 objects

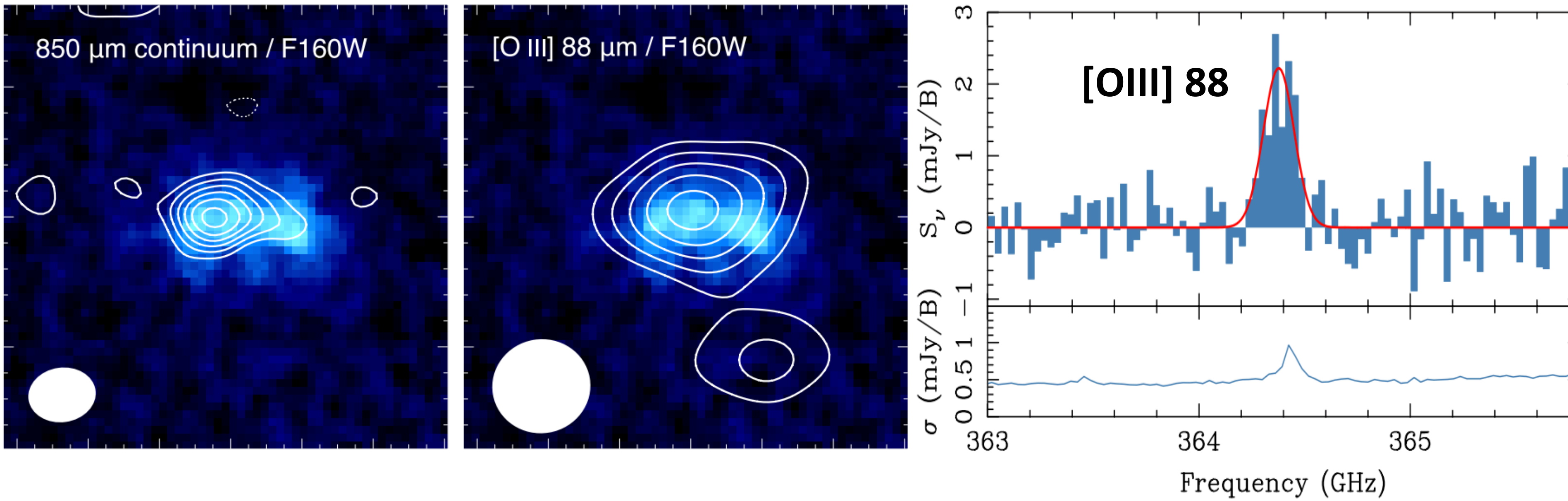
# The most distant galaxy with a spectral line: MACS1149-JD1 at z = 9.11




✓ SED analyses suggest that JD1 has initiated its star formation activity at **250 Myr after the Big Bang (z ~ 15)**

# A lensed galaxy with [OIII] 88μm and dust: MACS0416_Y1 at z = 8.31

Tamura+18

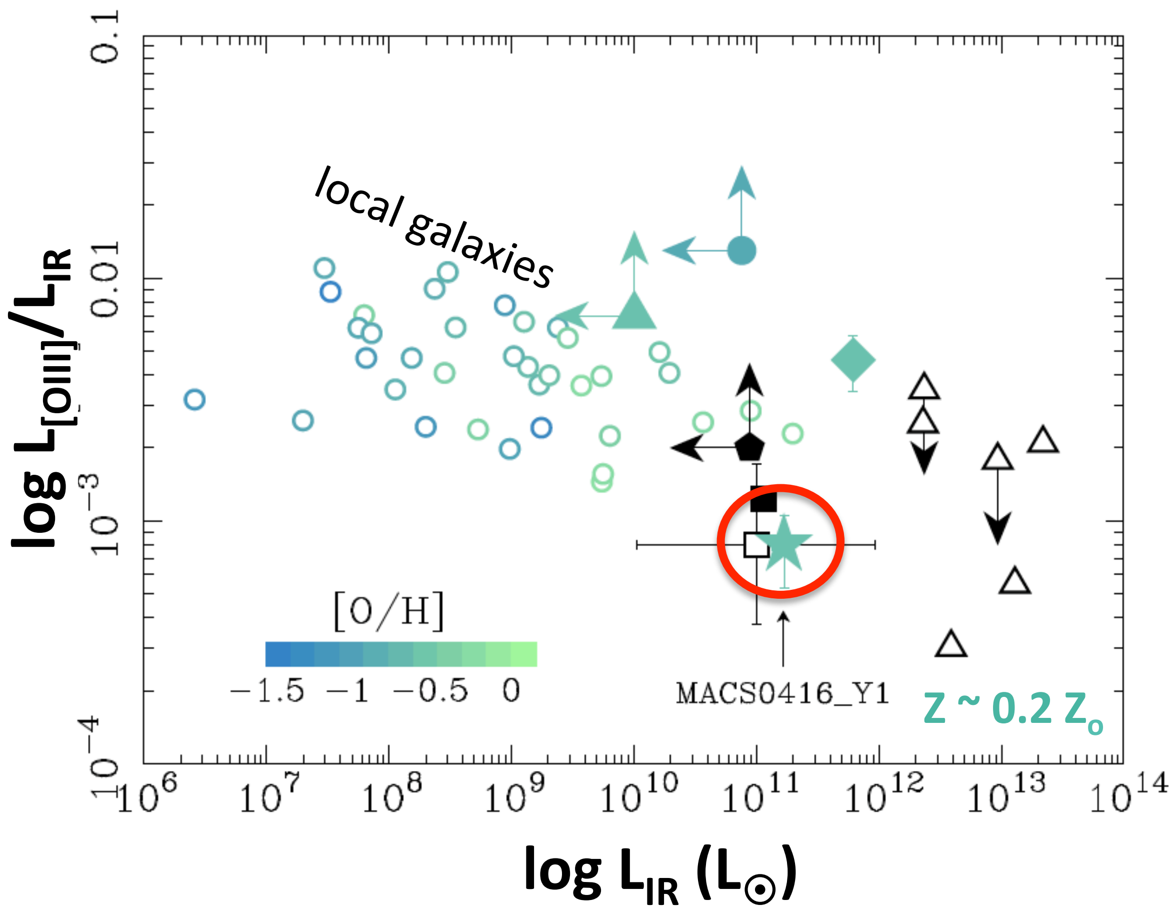



- ✓ $L_{TIR}$ ~ 1.7 x $10^{11}$ $L_\odot$ (MBB; $\beta_d$ = 1.5, $T_d$ = 50 K)
- ✓ Dust mass ~ 4 x $10^6$ $M_\odot$

$$\kappa = \kappa_0(\mu/\nu_0)^{\beta_{\rm d}}$$

$$\kappa_{\rm d}(850\ \mu{\rm m}) = 0.15\ {\rm m}^2\ {\rm kg}^{-1}$$ (Dunne+03)

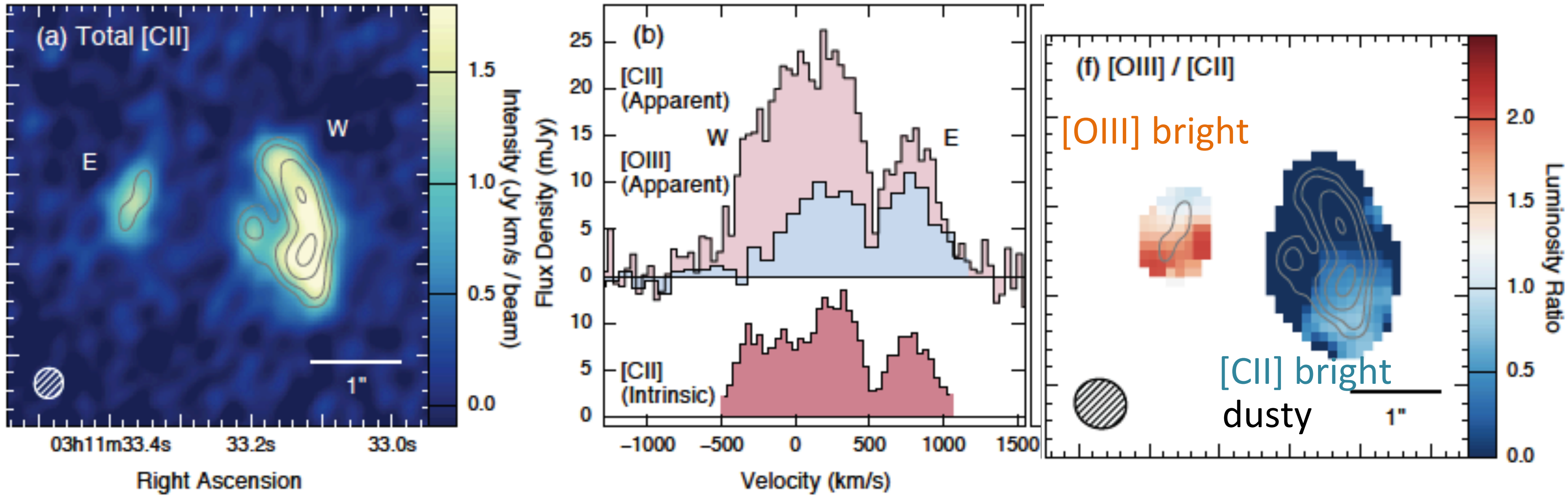
# A lensed galaxy with [OIII] 88μm and dust: MACS0416_Y1 at z = 8.31




✓ $L_{[OIII]}/L_{TIR}$ ~ $10^{-3}$ is comparable to <u>local spirals</u> or <u>dusty starbursts</u>

# A pair SMG at z = 6.90: SPT 058-0311

**Marrone+17, Nature**




- ✓ SPT survey has discovered a bright ($L_{TIR}$ ~ $10^{13}$ $L_o$) SMG → ALMA follow-up
- ✓ A pair SMG with different [OIII]/[CII] or [CII]/IR ratios
  → ALMA's high angular resolution is important

# ``Big Three Dragons (大三元)'' at z = 7.15

**Hashimoto+18b *submitted***

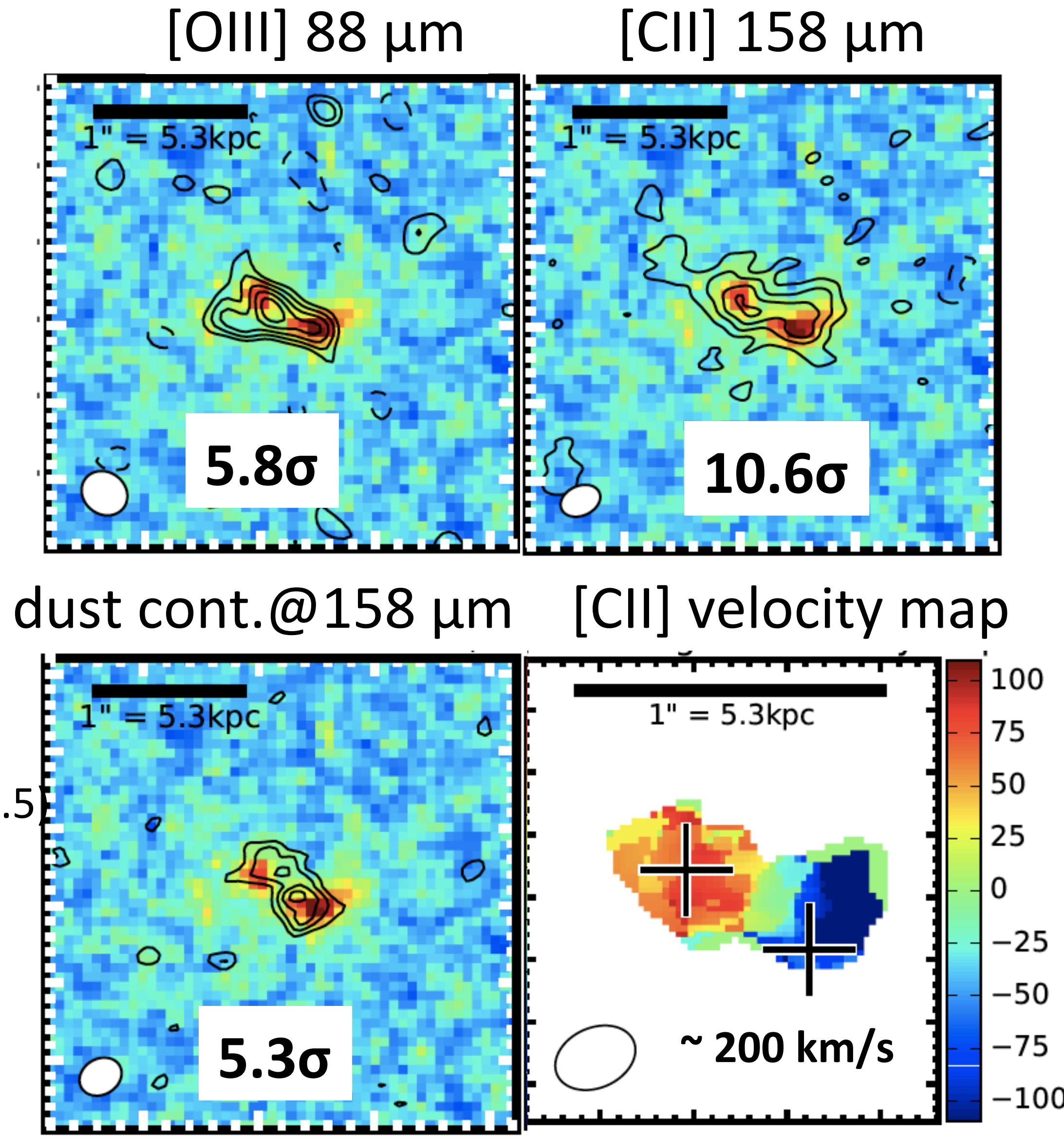
✓ The first complete set of [OIII], [CII], and dust
→ [OIII]/[CII] ~ 2


✓ The most distant velocity gradient

✓ $L_{TIR}$ ~ 6 x $10^{11}$ $L_{\odot}$ ($T_d$ = 50 K $\beta_d$ = 1.5)

✓ large SFR ~ 150 $M_{\odot}$/yr

➔ <u>A merger-induced starburst</u>



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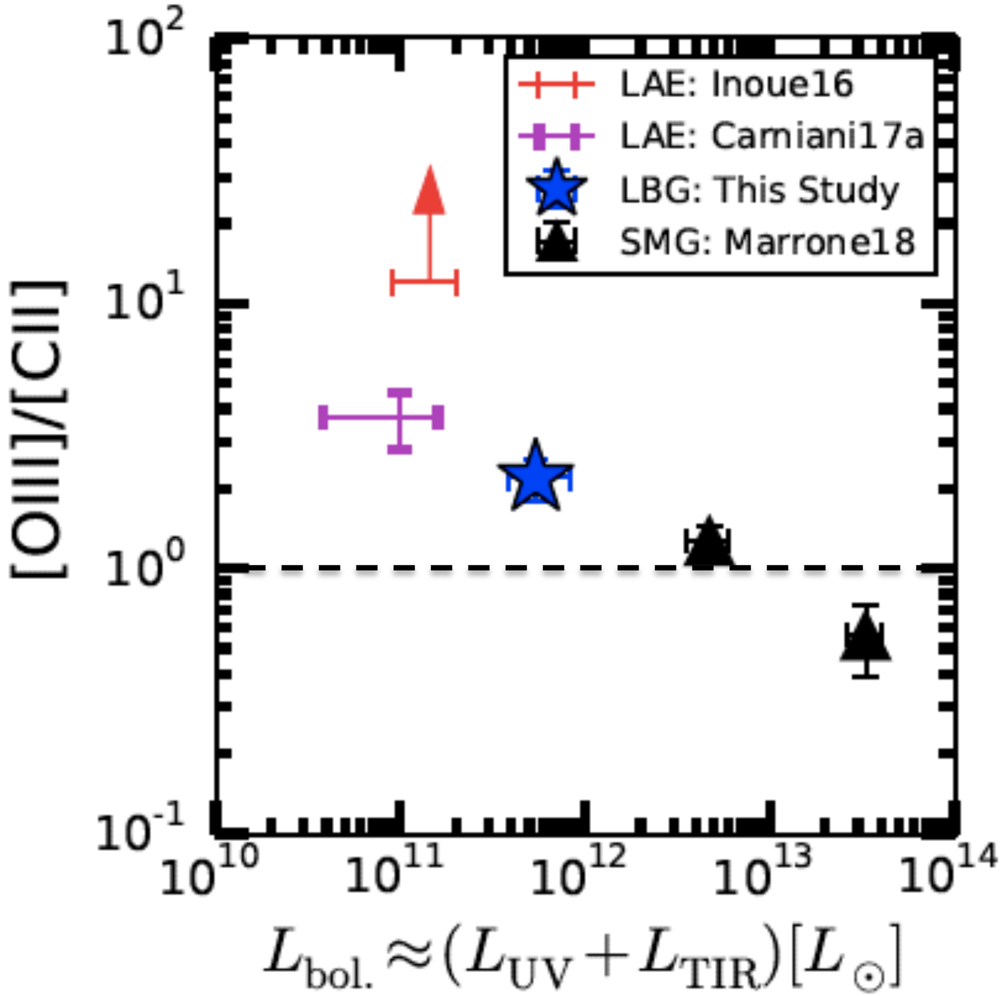
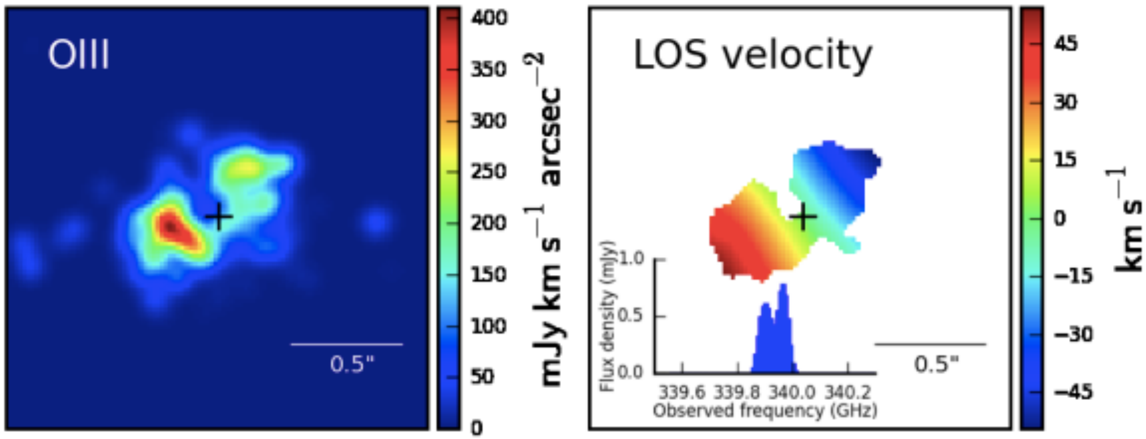



✓ [OIII]/[CII] luminosity ratio seems to be anti-correlate with $L_{\rm bol.}$

→ Low-mass galaxies have low metallicity and/or high ionization parameter (e.g. Harikane+18, Nakajima & Ouchi 14)

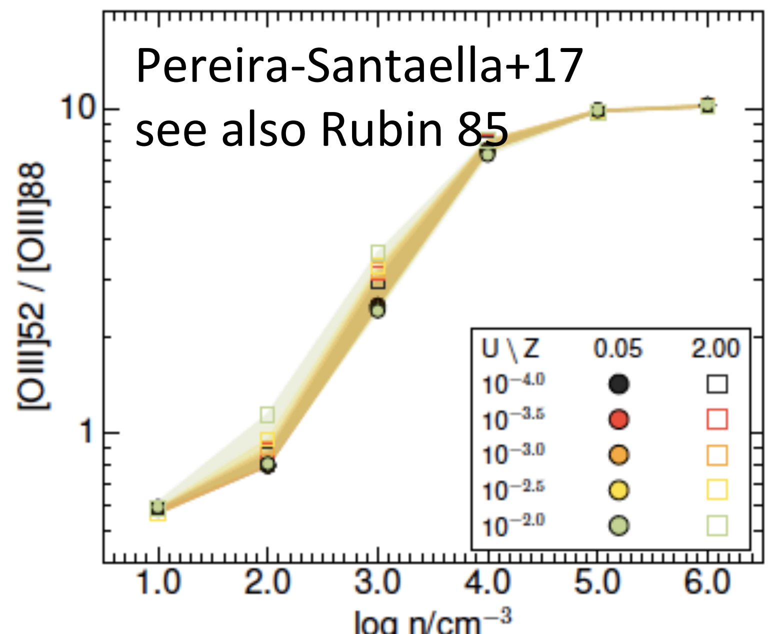
# Future plans

- [OIII] high angular resolution observations (morphology/kinematics)



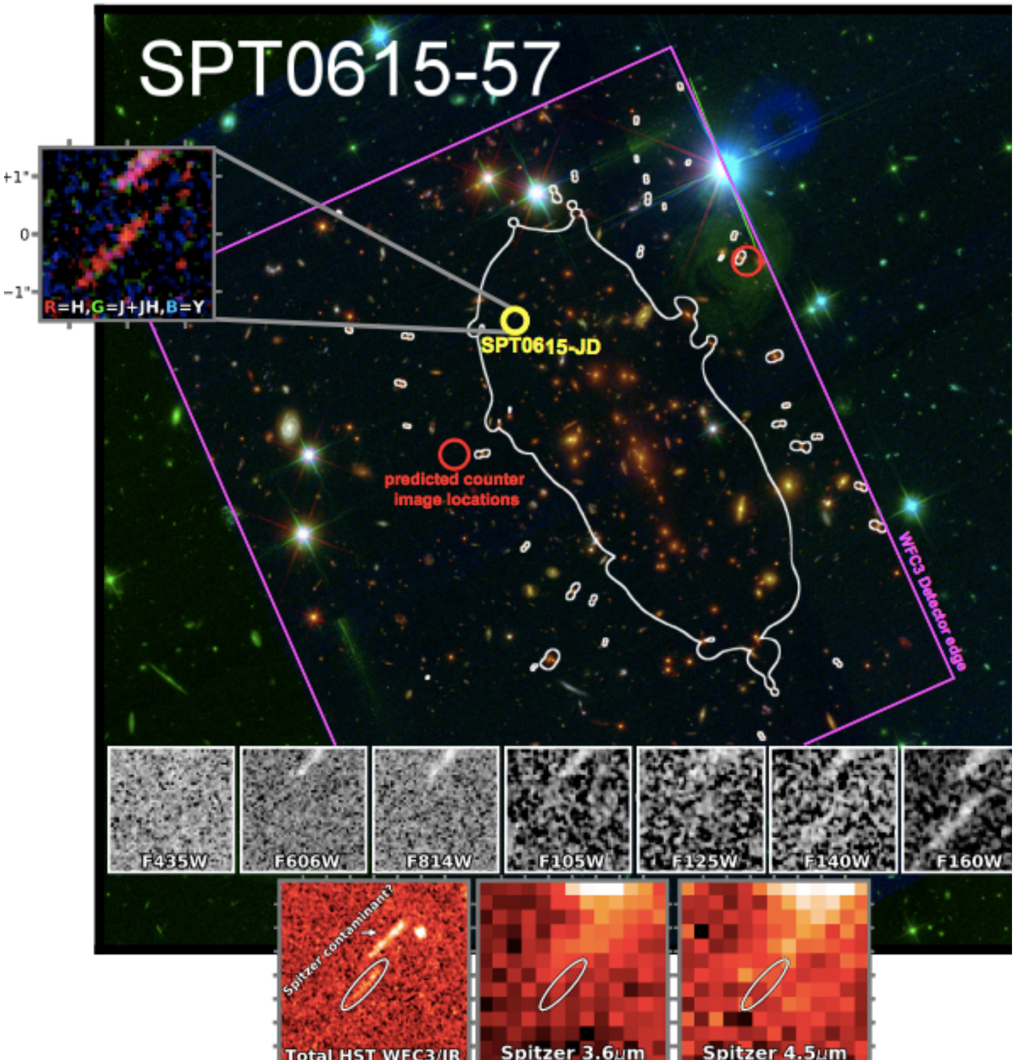

Moriwaki+18
sub-kpc scale resolutions
JD1 (Cy 6 A T. Hashimoto)
Y1 (Cy 6 A Y. Tamura )

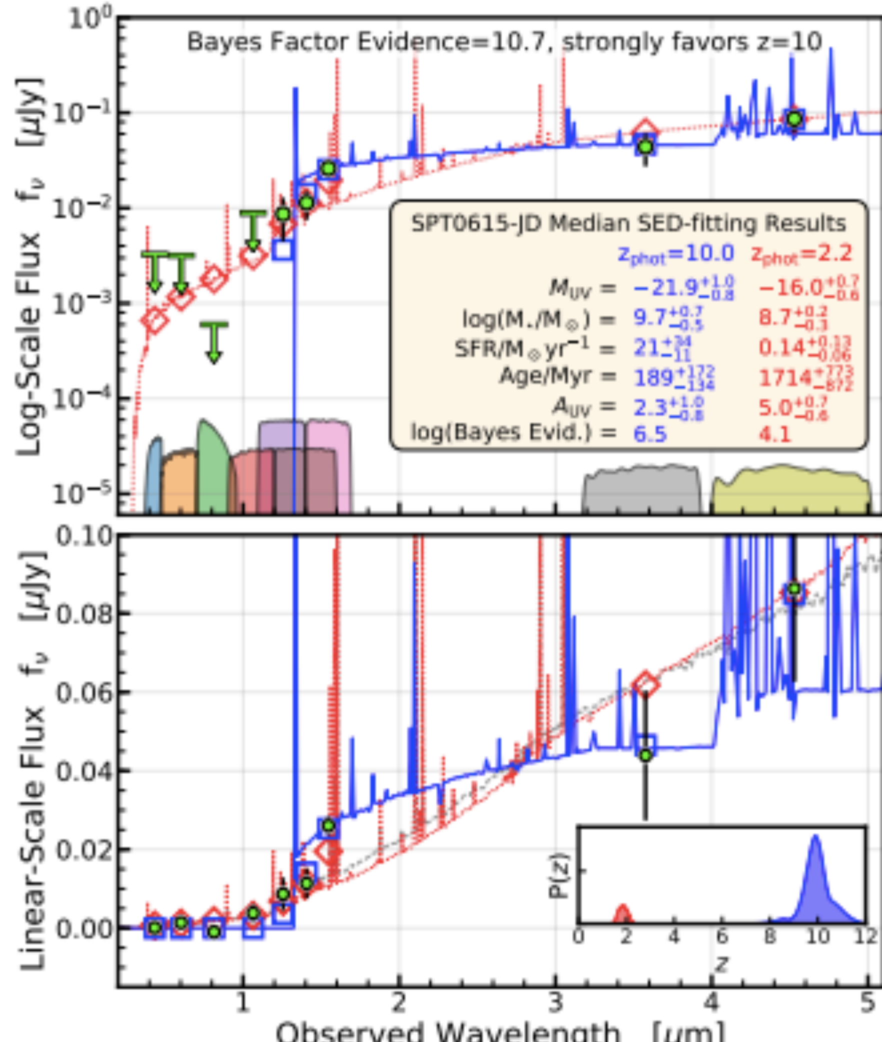
- Multiple lines to understand ISM
  B14-65666
  [OIII] 52 (Cy 6 B H. Mastuo)
  CO(7-6) (Cy 6 B T. Hashimoto)



# Future plans

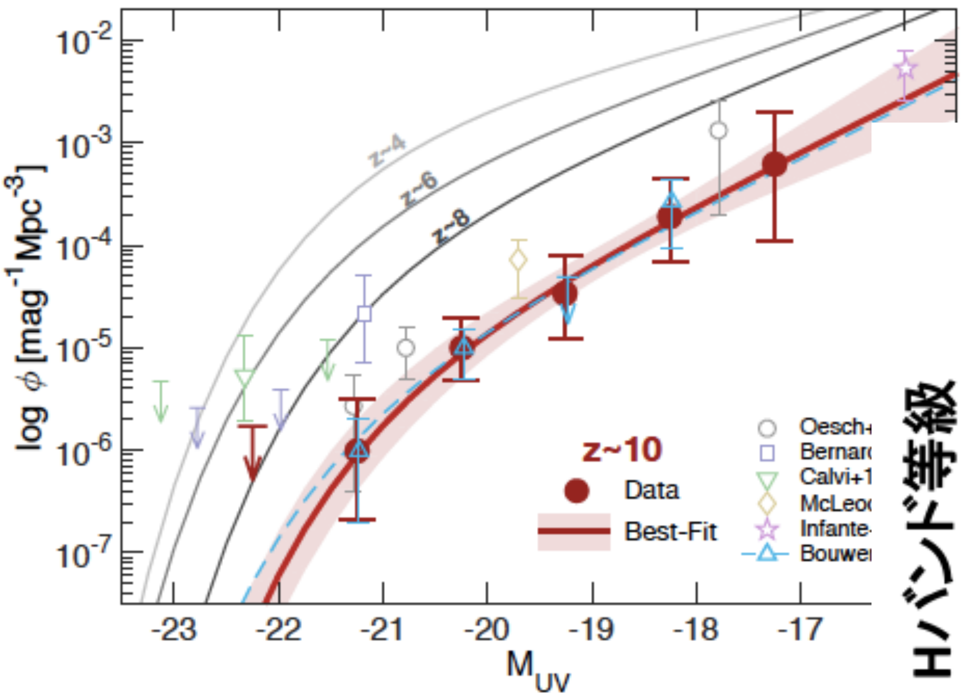
- ALMA [OIII] 88 for a lensed z ~ 10 galaxy (Cy6 A  Y. Tamura)

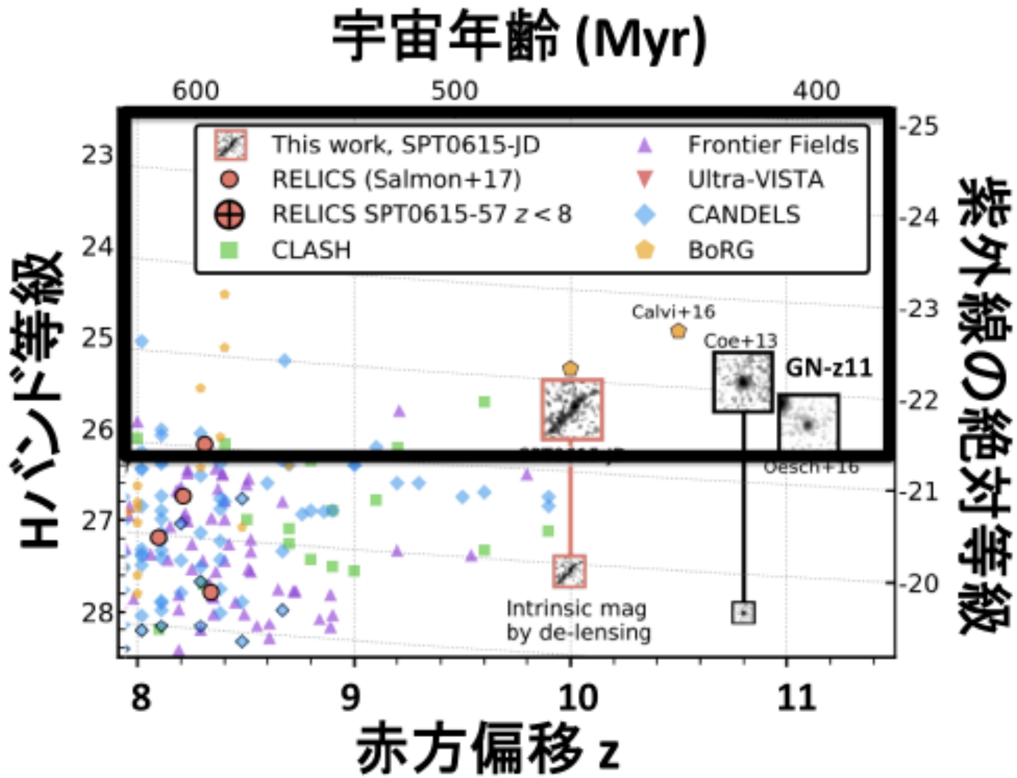


# Future plans

- A possible Cy 7 large program for z = 8 – 10 galaxies (Hashimoto)




-Strong UV LF evolution from z = 8 – 10

-~20 LBGs at $z_{ph}$ = 8 – 11 with H < 26.0 mag (Inoue+14)