First Identification of 10-kpc scale [CII] Halo around Star-forming Galaxies at $z = 5 - 7$

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in collaboration with

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arXiv: 190206760F
Outline

- Stacking Results
  
  Fujimoto et al. 2019  (arXiv: 190206760F)

- Individual Results
  
  Fujimoto et al. in prep.

- Future Prospects with ELT
CGM Metal-Enrichment in the Early Universe

Pure Feedback Mechanism

circum-galactic medium (CGM)
galaxy
Diffuse gas
Accreting gas
Recy
gas
Outflows

15 kpc
300 kpc
Tumlinson+17
- Hydrogen spreads over CGM

- Dust & [CII] 158um … Good probe for CGM metal enrichment

**poor sensitivity** … **Stacking**

e.g., Capak+15, Knudsen+16, Pentericci+16, Jones+17, Carniani+18, Smit+18
Data & Sample

ALMA [CII] 158um line observations: our data + archive

i) [CII] detected at z > 5
ii) SFR < 100 M. / yr
iii) Not AGN
iv) Not Lyman-alpha blob (e.g., Himiko, CR7)
v) Not gravitationally lensed system
vi) FWHM of [C II] line > 80 km/s

18 (12) **normal** star-forming galaxies at z=5.15-7.14 (with HST data)
SFR ~ 10 - 70 M./yr

--- Previously reported ---

--- New ---
ALMA Deepest Imaging for z~6 Galaxies

- Dust continuum: ~10σ detection, compact morphology
- [CII] line: 20σ detection
- Extended structure up to radius ~ 10 kpc (9.2σ)

see also Michele’s talk
Careful Tests

- ~10-kpc scale extended structure appears in any cases
- [CII]: extended more than rest-UV & FIR
Two Questions

1. How carbon was enriched in ~ 10-kpc scale?

2. What powers C+ emission? photoionization, (SF-driven) outflow, inflow ...?

see also Michele’s talk

- [CII]: extended more than rest-UV & FIR
L\(_{\text{[CII]}}\) / SFR ratio \(\sim 1\) dex higher than low-mass galaxies

How Carbon Enriched?

1) Satellite galaxies
2) past outflow activity

from Diaz-Santos+13, Delooze+14
How Carbon Enriched?

1) Satellite galaxies

2) Past outflow activity

Evidence of outflow remnants in early galaxies

$L_{[\text{CII}]} / \text{SFR} \sim 1 \text{ dex higher than low-mass galaxies}$

from Diaz-Santos+13, Delooze+14
Comparison with Model

- rest-UV & FIR continuum … reproduced
- [CII] … Not reproduced
- [CII] halo → Challenging the current galaxy formation models
- Consistent with Lya Halo Profile
- Central: Re ~ 1.1 +/- 0.1 kpc, Halo: Re ~ 5.6 +/- 0.2 kpc
- Individual comparison is essential
Individual Results
Future Prospects
Individual Halo with ELT

Detecting halo ($r \sim 10$ kpc) emission at $z \sim 6$ ...

- Lya: $\sim 0.6$ hour*
- CIII, CIV: $\sim 10$ hour*

*Assumptions:
S/N $\sim 3$ [arcsec$^{-2}$]
Line luminosities … Stark+16
Radial profile … Leclercq+17

- 2D (+3D) comparison of multi-phase halo gas structures
Summary

- Discovery of $r \sim 10$-kpc scale [CII] Halo statistically & individually
- [CII] halo …
  - Evidence of outflow remnants
  - Challenging current models
  - Potentially associated with Lya Halo
- Future with ELT … 2D (+3D) structure of multi-phase halo gas