ALMA による z = 6-9 銀河の性質と南極 THz 望遠鏡への期待

橋本拓也

筑波大学 宇宙史研究センター
テニュアトラック助教 (卓越研究員)

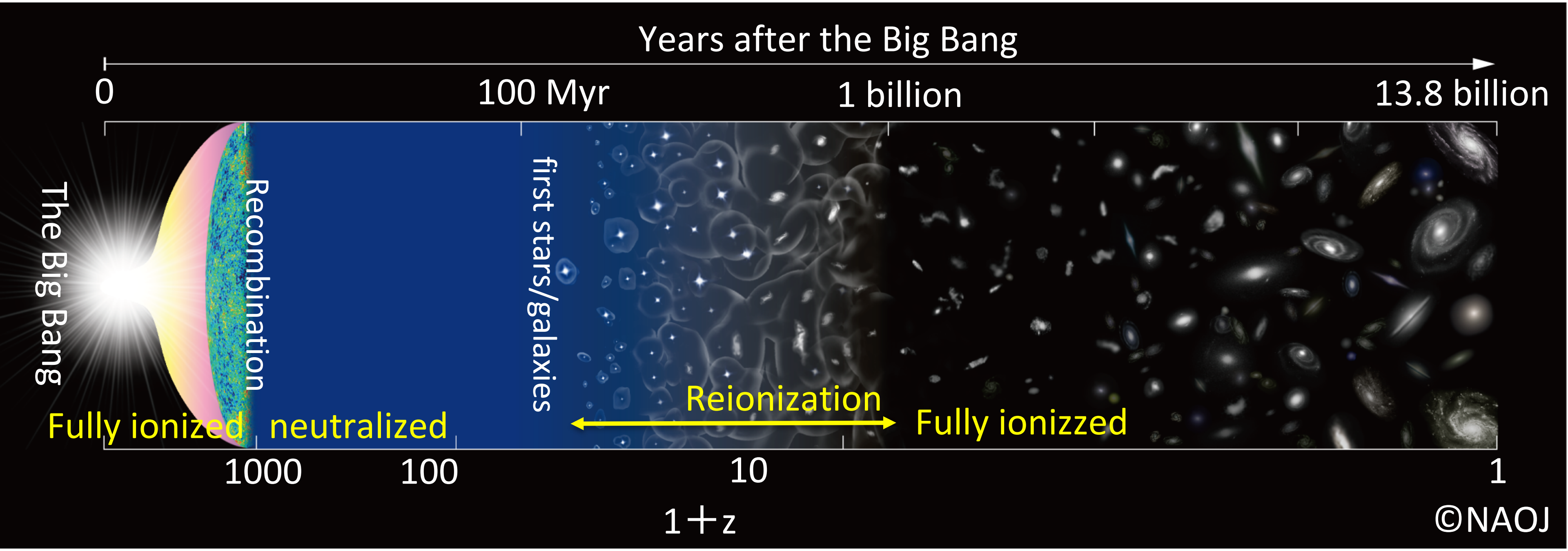
Outline

- **Introduction**
  - Cosmic reionization
  - Galaxies in the epoch of reionization (EoR)
    - Spectroscopy
- **Rest-frame FIR properties at z > 7 with ALMA**
  - **Case study:** properties of a z = 9.1 [OIII] 88μm emitter
  - **Statistics:** High ratios of L[OIII] 88 μm/L[CII] 158 μm in high-z LAEs/LBGs
- **(Some thoughts on AAT)**

Outline

- **Introduction**
  - Cosmic reionization
  - Galaxies in the epoch of reionization (EoR)
    - Spectroscopy
- **Rest-frame FIR properties at z > 7 with ALMA**
  - **Case study:**
    properties of a z = 9.1 [OIII] 88μm emitter
  - **Statistics:**
    High ratios of L[OIII] 88 μm/L[CII] 158 μm
    in high-z LAEs/LBGs
- **Some thoughts on AAT**

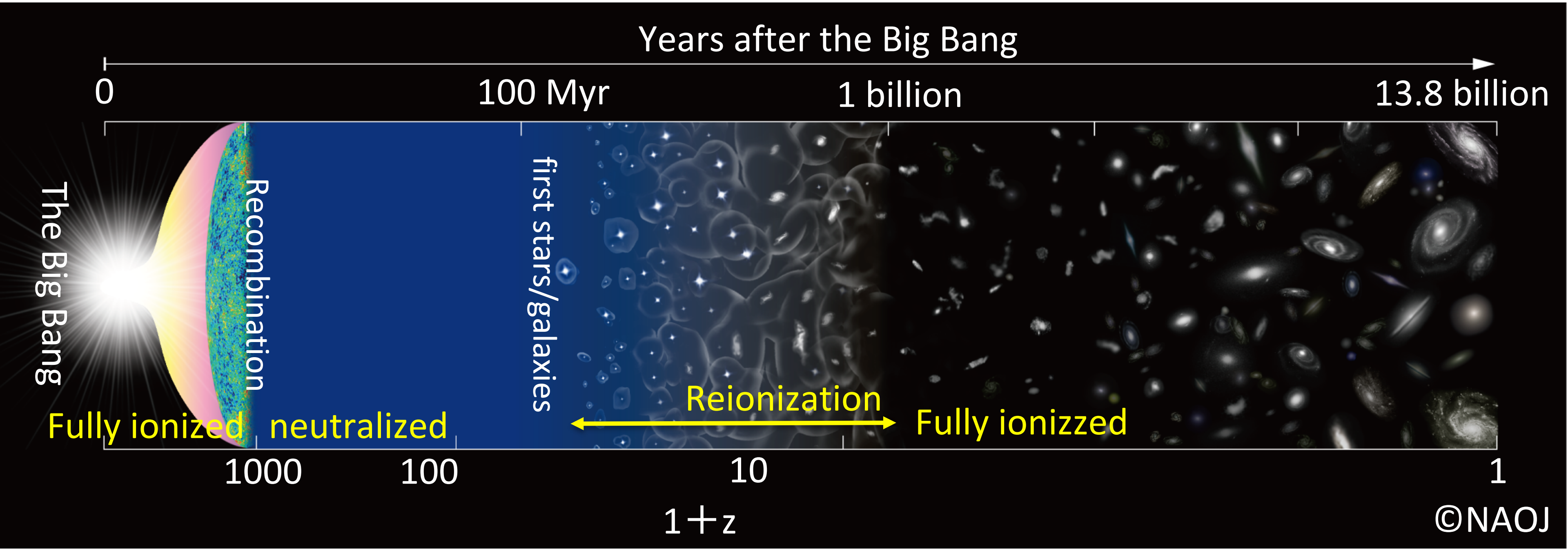
Cosmic Reionization



- **Reionization**: $z \sim 20 - 6$ ($t_{univ} \sim$ 200 Myr - 1 Gyr)
- Hydrogen ionizing photon (LyC: $\lambda < 912$ Å or $E > 13.6$ eV)

- **Key questions**
  - What is the main driver of reionization?
  - How, when and where reionization has processed ?

Cosmic Reionization

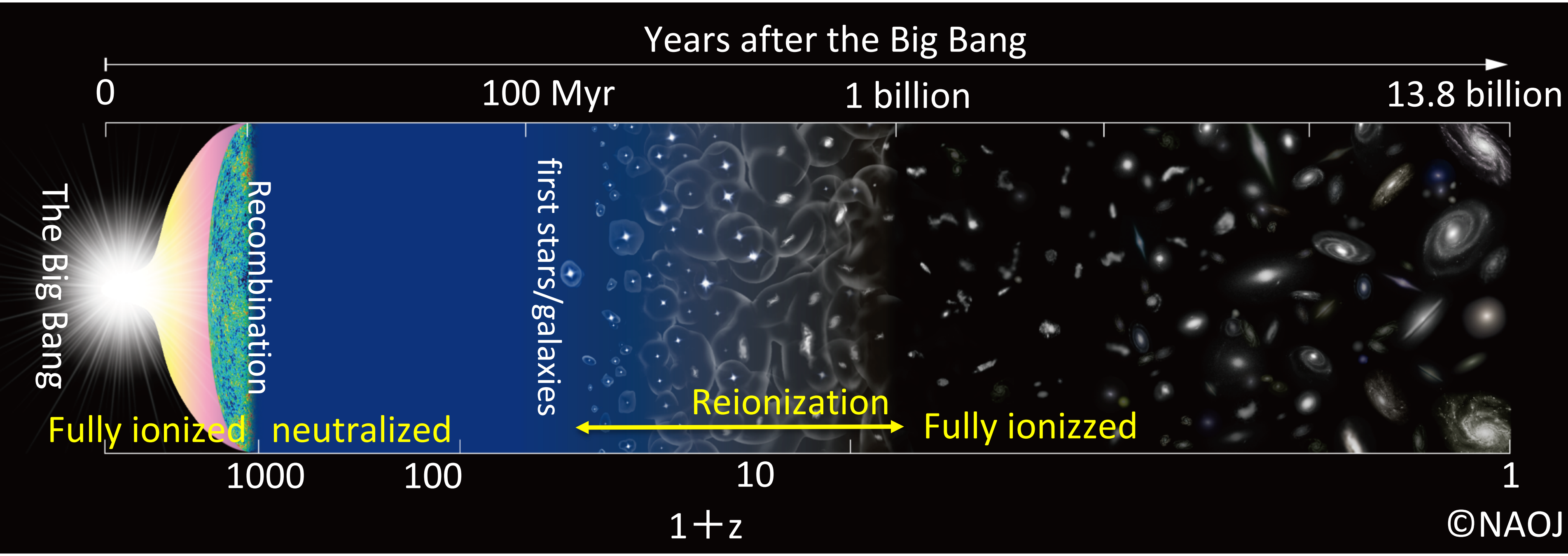


- **Reionization**: z ~ 20 - 6 (t_{univ} ~ 200 Myr - 1 Gyr)
- Hydrogen ionizing photon (LyC: λ < 912 Å or E > 13.6 eV)
- **Key questions**

  - What is the main driver of reionization? | cf., **blue compact galaxies** |

  → **Recent consensus: abundant UV star-forming galaxies are sufficient without demanding Pop III stars (e.g., Robertson+15)**

Cosmic Reionization



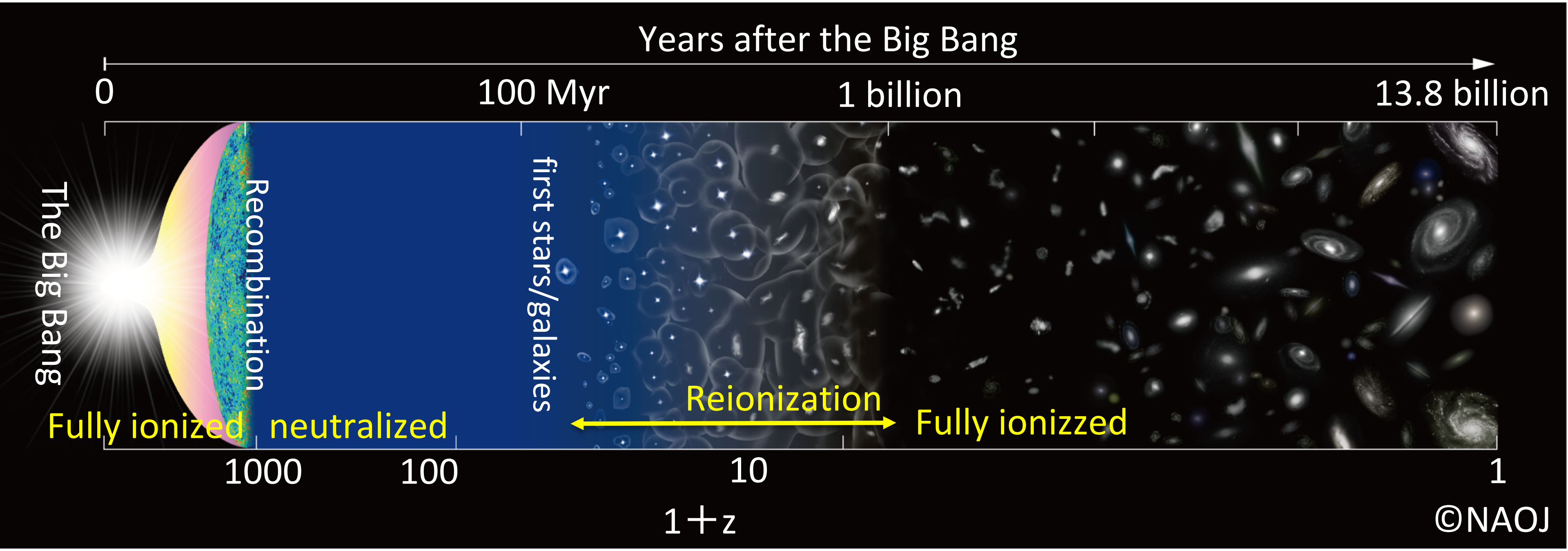
- **Reionization**: z ~ 20 - 6 (t_{univ} ~ 200 Myr - 1 Gyr)
- Hydrogen ionizing photon (LyC: λ < 912 Å or E > 13.6 eV)
- **Key questions**

  - What is the main driver of reionization?

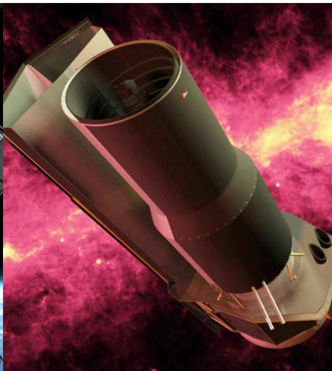
  - How, when and where reionization has processed ?

    → future 21cm observations in the EoR (割愛)

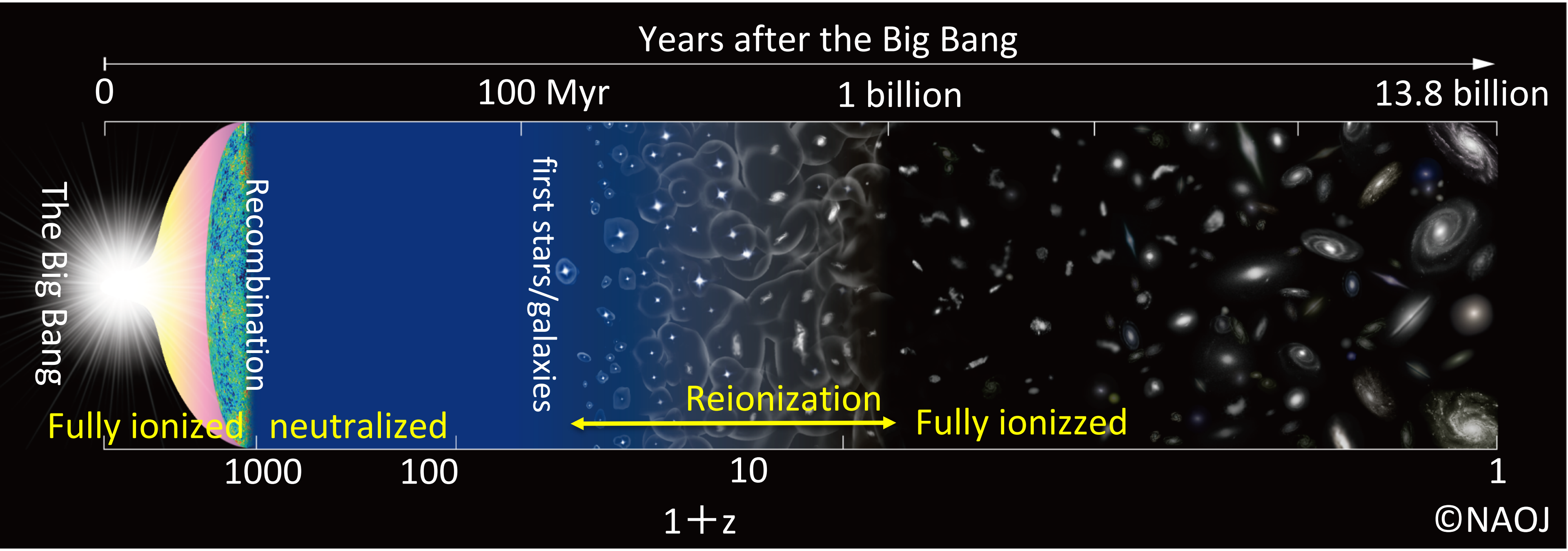
Galaxies in the Epoch of Reionization



- Galaxy candidates at z ≈ 8 - 11 owing to *HST* and *Spitzer*
- Statistical properties (UV LF, SFRD)



Galaxies in the Epoch of Reionization

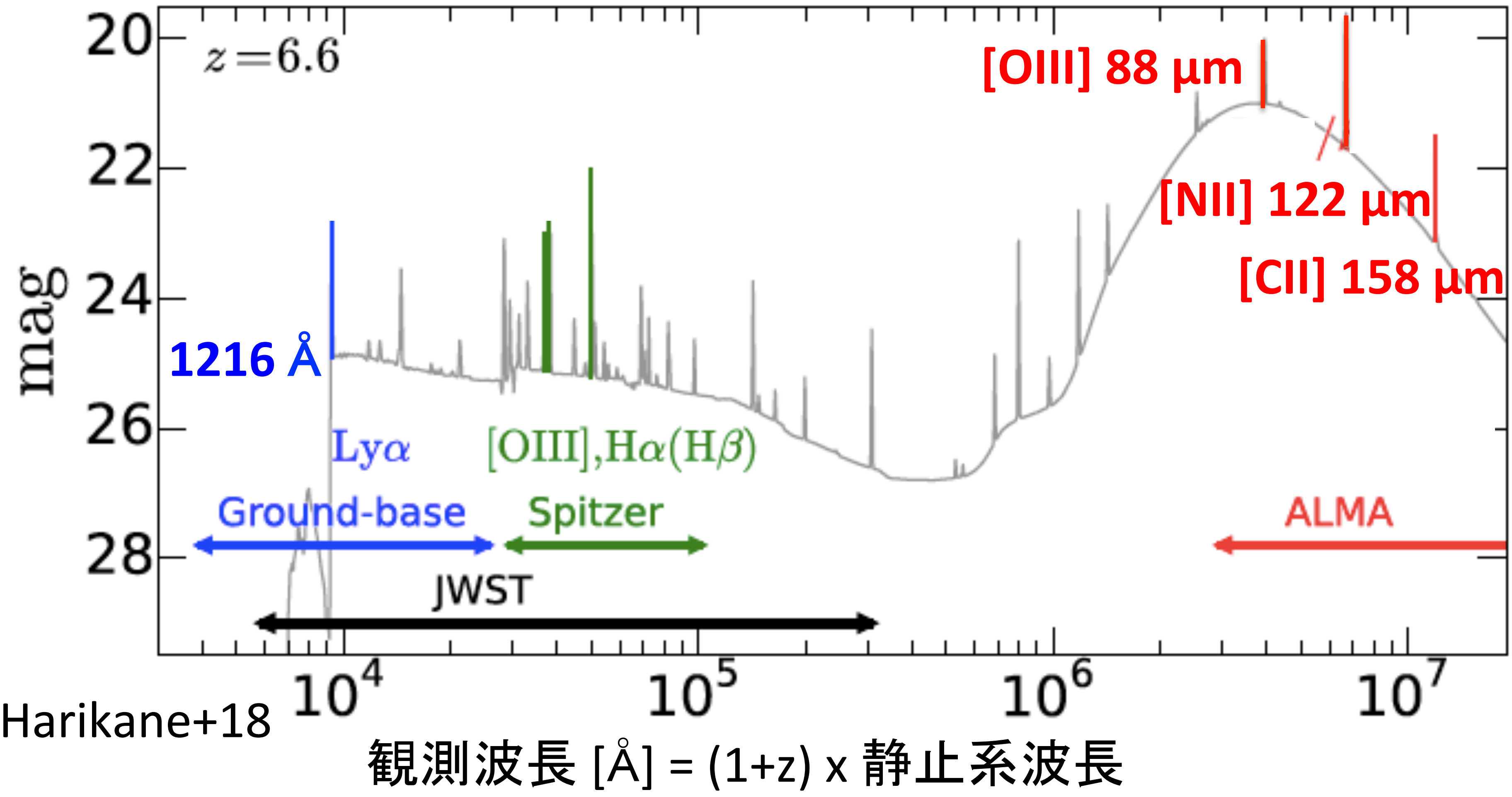


- Spectroscopic properties in the EoR are yet to be constrained **(redshift identification, *Z*, *U*, n_e)**
- **Galaxy formation and evolution**
  - Ancestors of present-day galaxies
  - Origin of heavy elements (O, C, N etc.) and cosmic dust
  - Star forming activity & ISM properties (e.g. f_{esc}, Z, U, n_e)

Spectroscopy at z > 7

- Lyα is powerful at z up to ~ 7 (e.g. **VLT/MUSE**: Bacon+17, **Hashimoto+17b**)
- but strongly attenuated by the IGM at z > 7 (e.g. Stark+10, Pentericci+12)

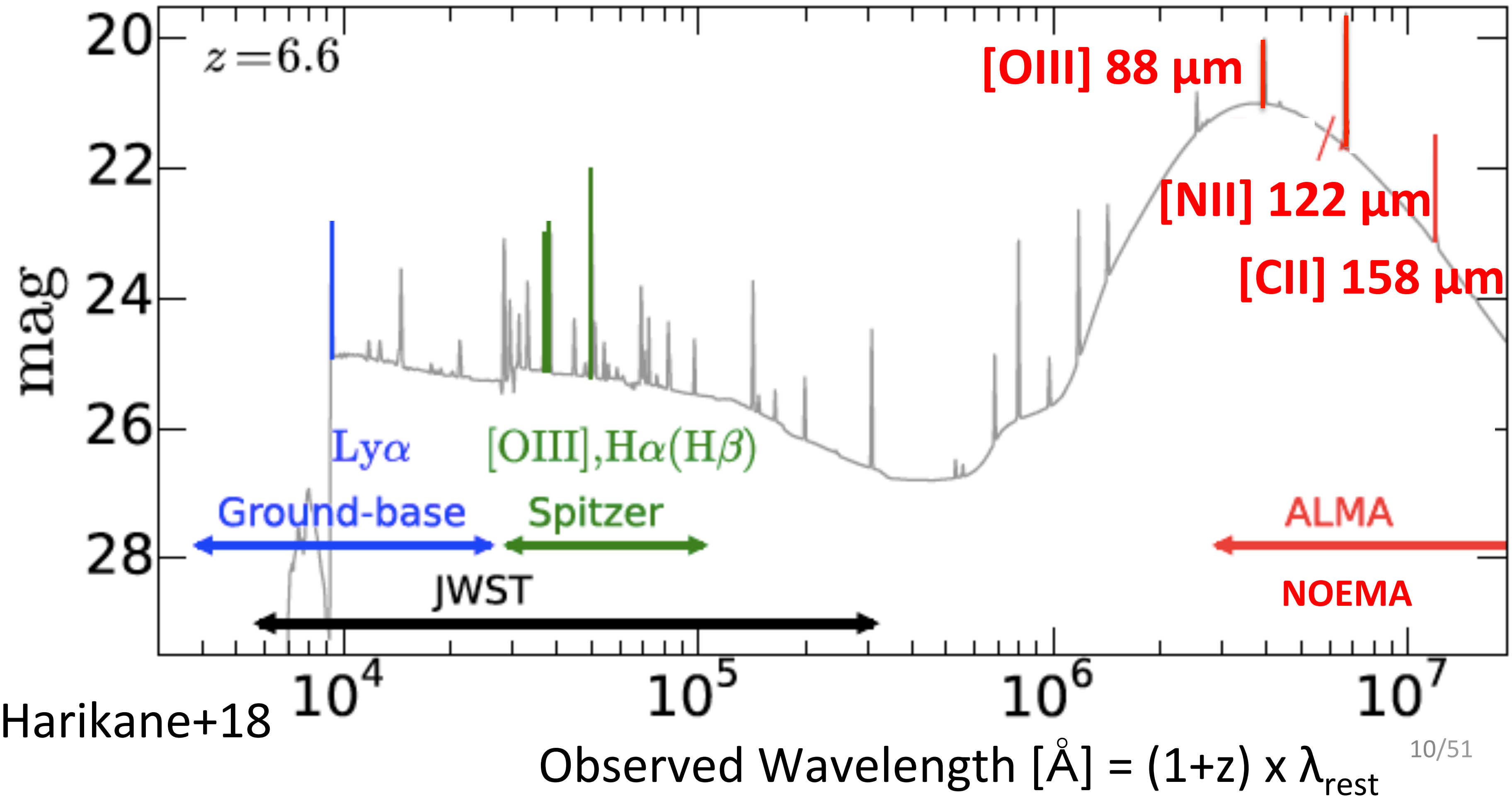
➔ ***Alternative emission line is essential***



Harikane+18

ALMA observations at z > 7

- **Far-infrared fine structure lines** are useful
  - metallicity, U, n_e (Nagao+12, Pereira-Santaella+18)
- **Dust continuum** can be simultaneously observed
  - star-formation activity (dust production/growth/destruction)

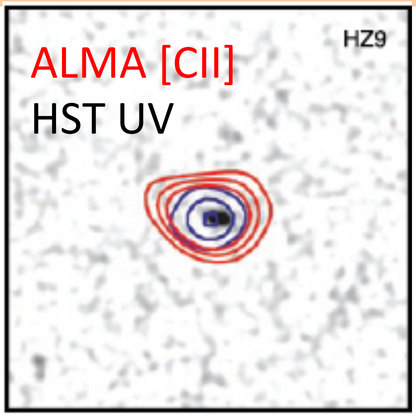


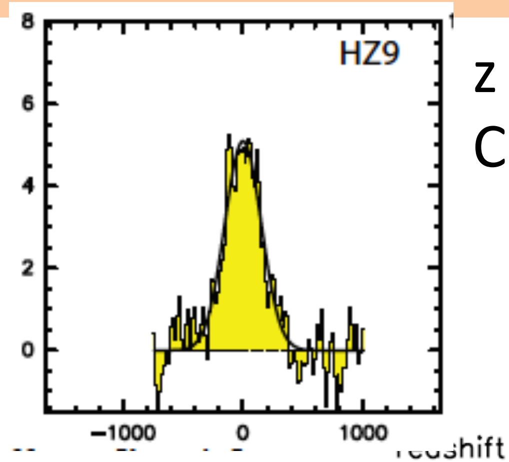
Harikane+18

A traditional tool at high-z: [CII] 158μm

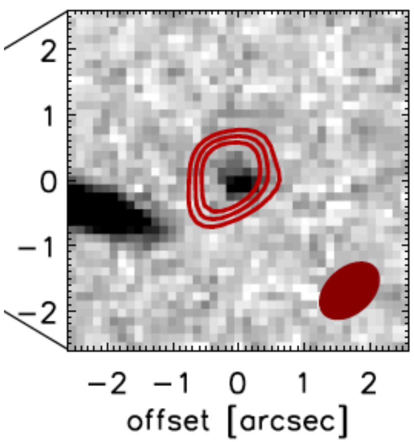
- ~20 [CII] detections at z ~ 5 - 7 galaxies (e.g. Carniani+17, Smit+18)
  Many detections in high-z QSOs

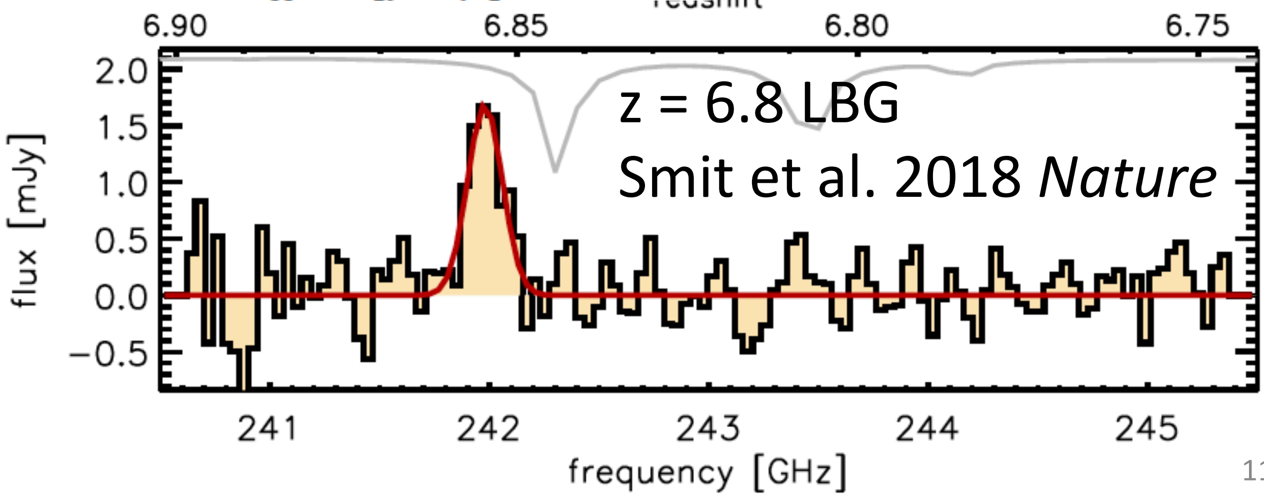
- Non-detections are reported at z > 7 (Ouchi+13, Ota+14)





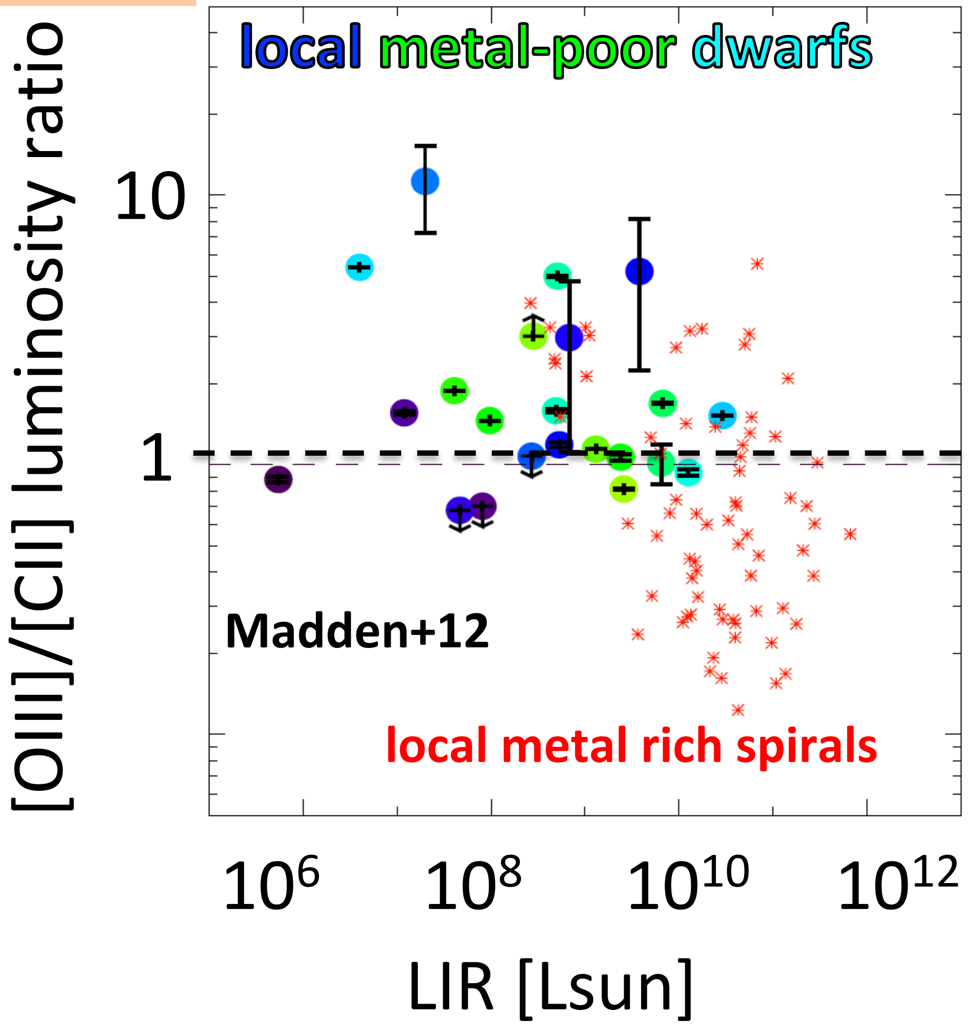
z = 5.5 LBG
Capak et al. 2015 *Nature*





[OIII] 88 µm in the local Universe

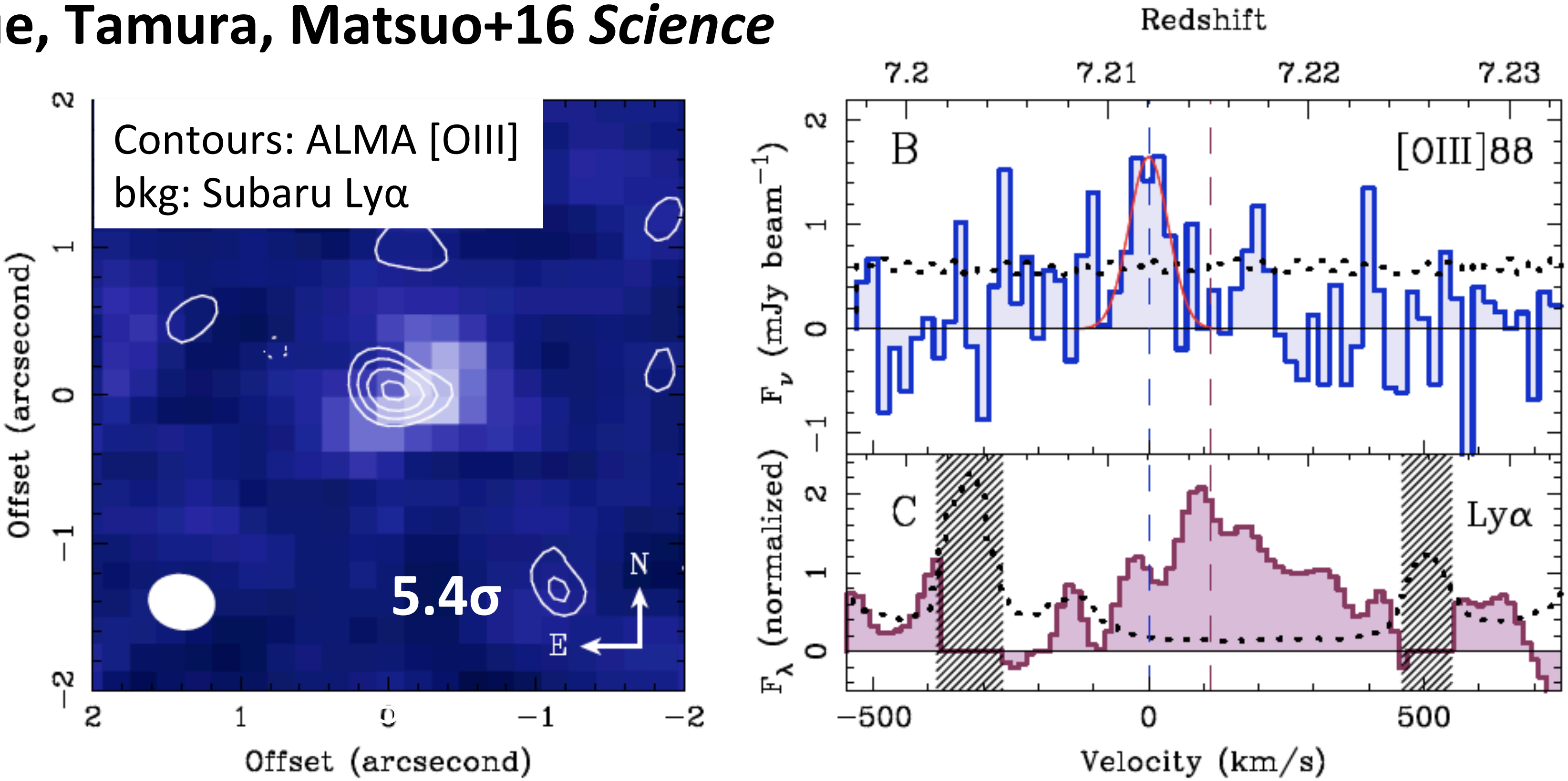
- *ISO* metal rich spirals, $L_{[OIII]} \approx 0.5 \times L_{[CII]}$ (e.g. Malhotra+01, Brauher+08)
- *Herschel* dwarf galaxies, $L_{[OIII]} \approx 2 \times L_{[CII]}$ (e.g. Madden+12, Cormier+15)
  Some objects have $L_{[OIII]} \approx 10 \times L_{[CII]}$



The first [OIII] 88 μm detection in the EoR

- LAE at z_{Lya} = 7.21 with EW_0(Lyα) = 33 Å (Shibuya+12)
  - ALMA Band 8 follow-up observations (PI. A. K. Inoue)

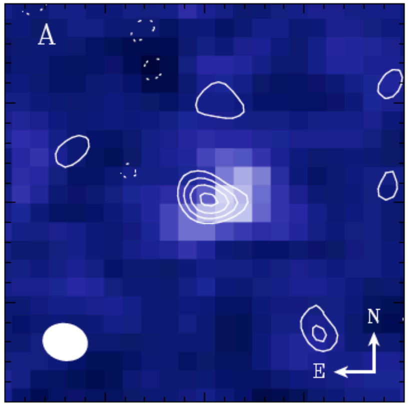
Inoue, Tamura, Matsuo+16 *Science*



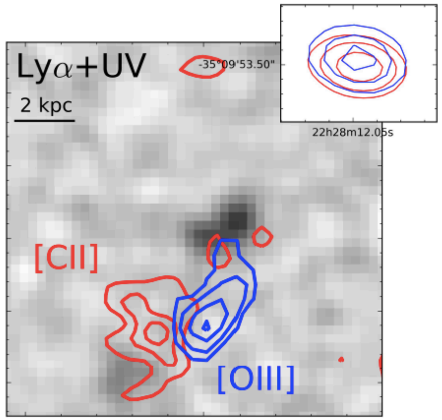
- Band 6 [CII] is undetected; **L[OIII]/L[CII] > 12 (3σ: later discussion)**
- This pioneering work opens a new window in studies of reionization

More than *N* > 15 [OIII] 88 μm in the EoR

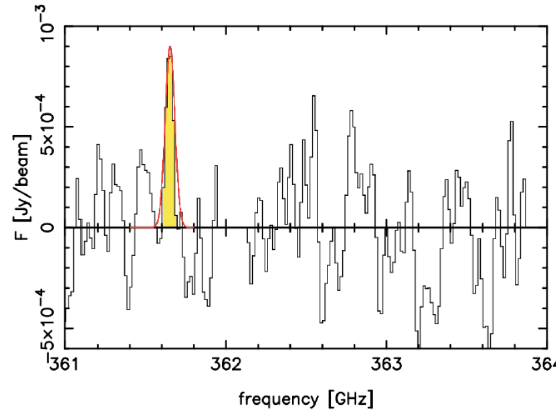
Inoue+16
LAE



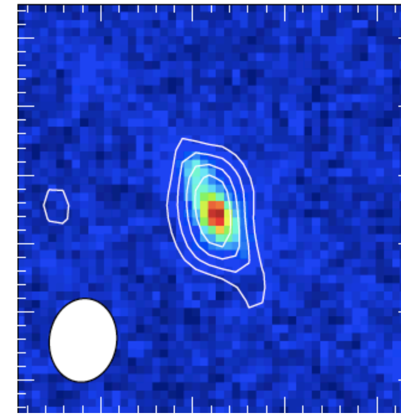
Carniani+17
LAE



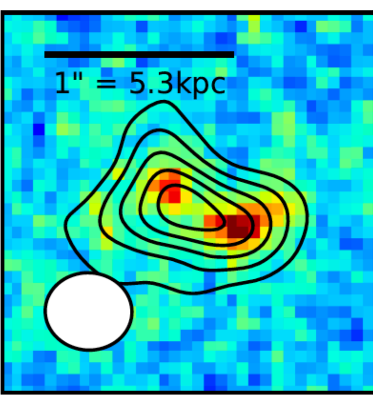
Laporte+17
LAE/LBG



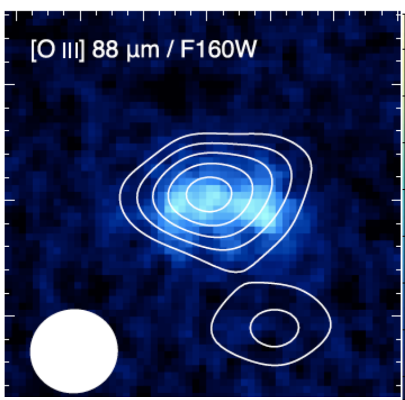
Hashimoto+18
L AE/LBG



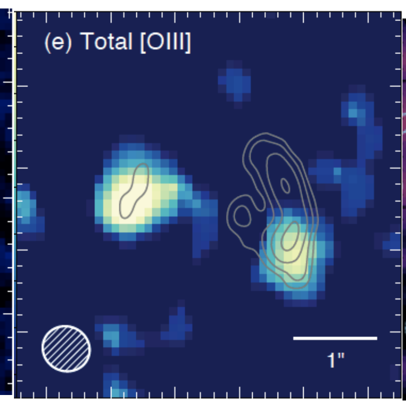
Hashimoto+19a
LAE/LBG



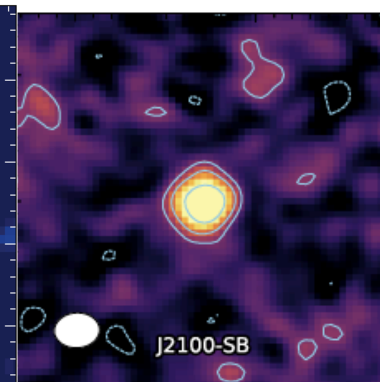
Tamura+19
LBG



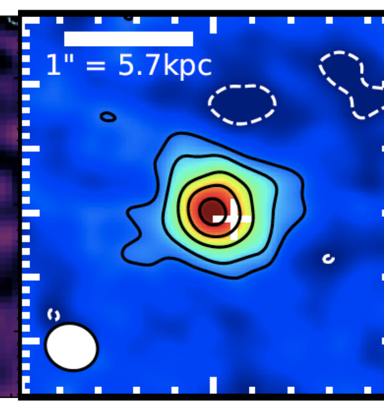
Marrone+18
pair-SMG



Walter+18
SMG and QSO



Hashimoto+19b
2 QSOs

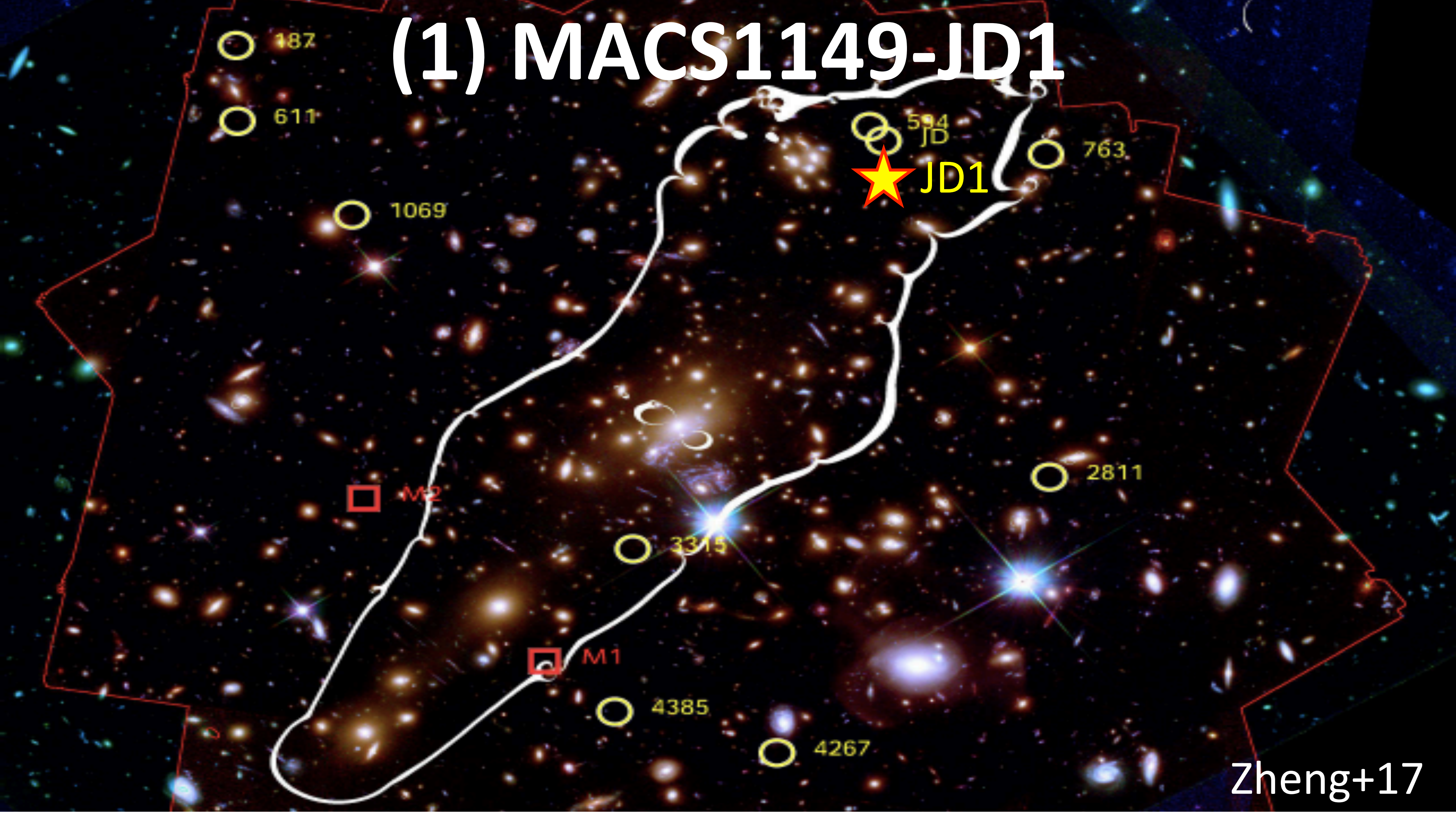


also Harikane+19; Sunaga+ in prep.

Outline

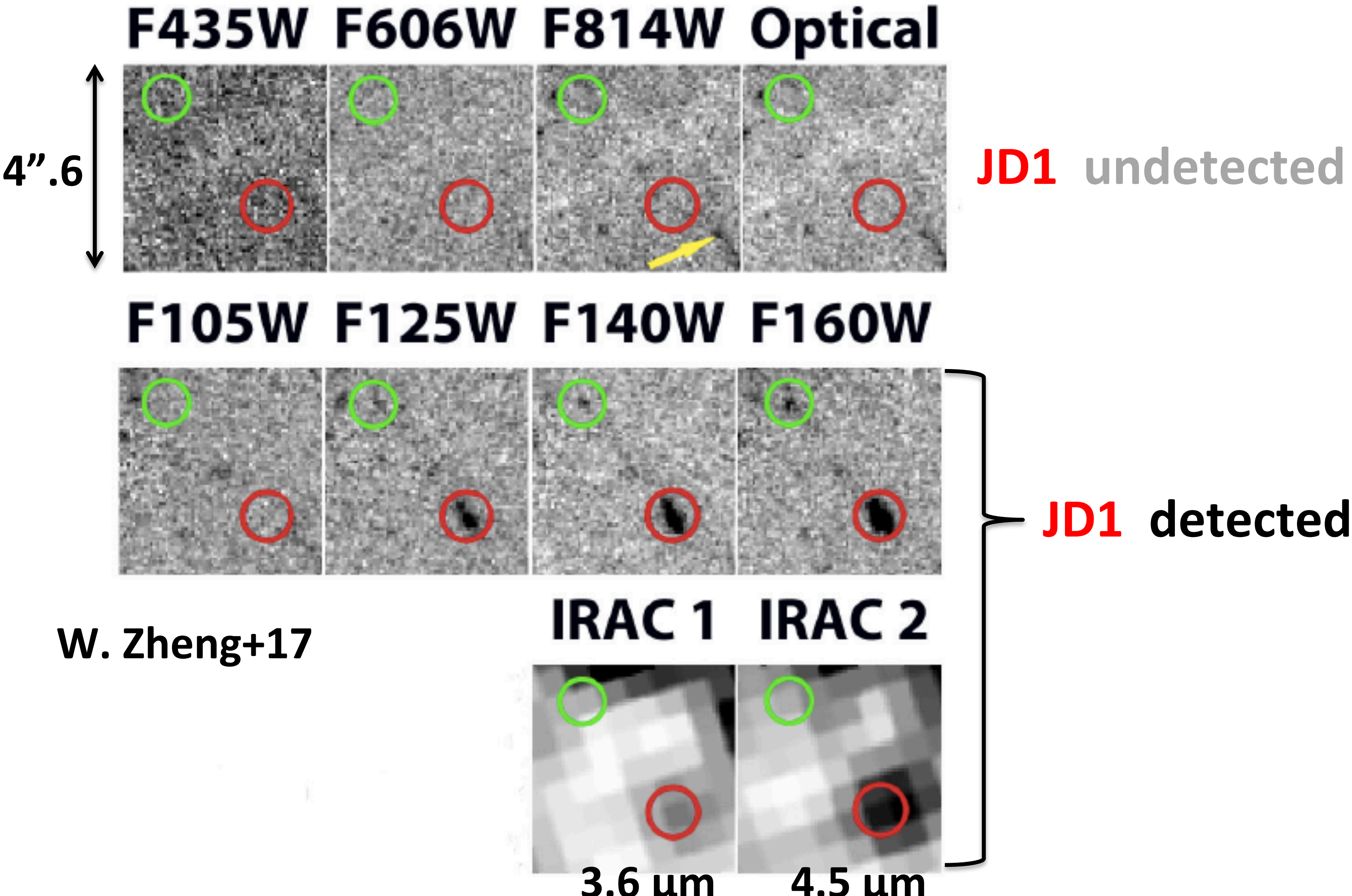
- **Introduction**
  - Cosmic reionization
  - Galaxies in the epoch of reionization (EoR)
    - Spectroscopy
- **Rest-frame FIR properties at z > 7 with ALMA**
  - **Case study:**
    properties of a z = 9.1 [OIII] 88μm emitter
  - **Statistics:**
    High ratios of L[OIII] 88 μm/L[CII] 158 μm
    in high-z LAEs/LBGs
- **Some thoughts on AAT**

(1) MACS1149-JD1



- A **lensed *J*-band dropout** galaxy (Zheng+12, *Nature*)
- Bright **(H=25.7)** with a magnification factor **(μ_g) ~ 10**
- One of the highest-z galaxy candidate accessible w. **ALMA**

HST and Spitzer/IRAC images of JD1

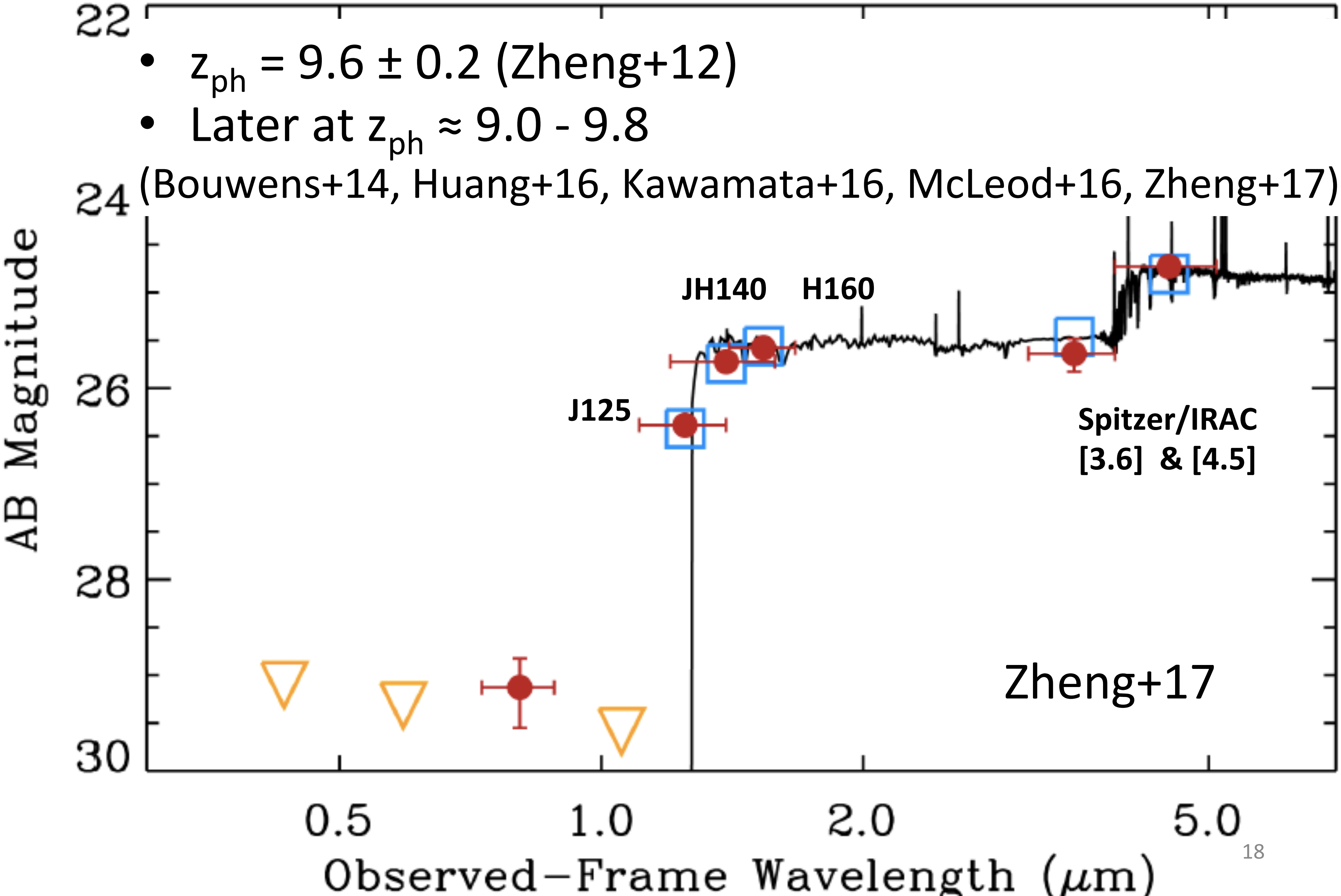


W. Zheng+17

SED of JD1

- z_{ph} = 9.6 ± 0.2 (Zheng+12)
- Later at z_{ph} ≈ 9.0 - 9.8

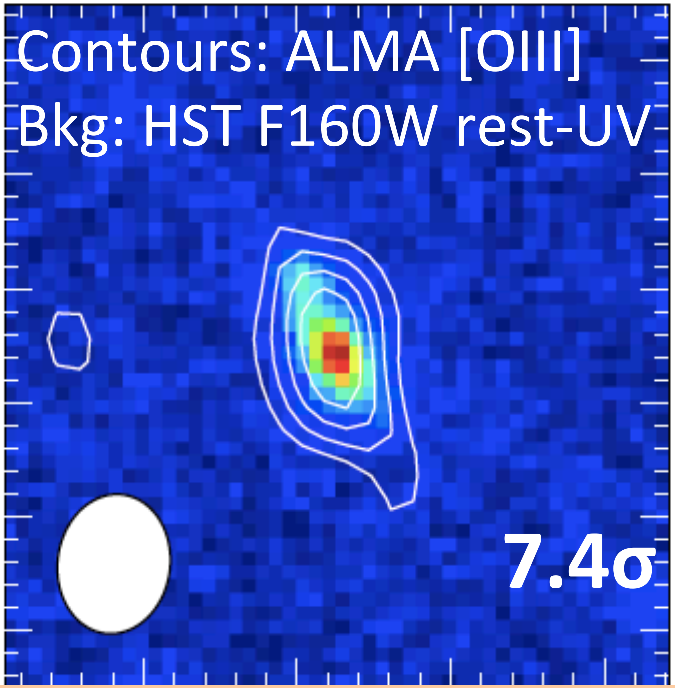
(Bouwens+14, Huang+16, Kawamata+16, McLeod+16, Zheng+17)

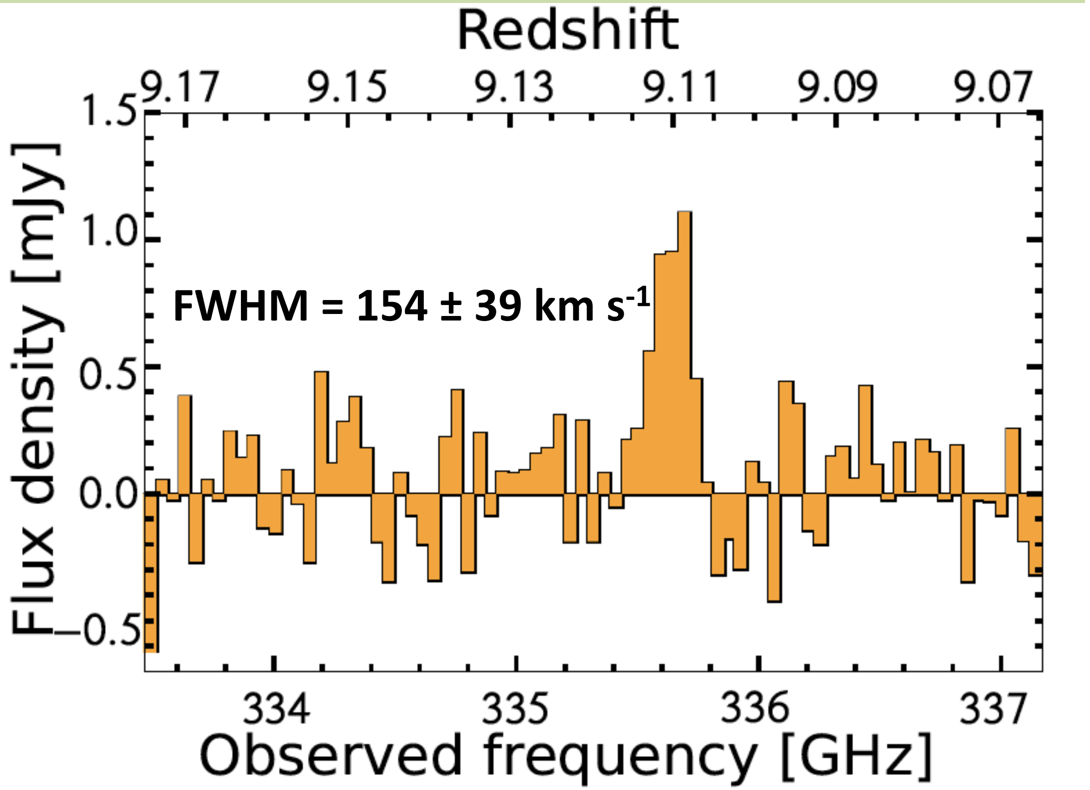


[OIII] 88μm detection at $z = 9.11$

- ALMA Band 7 in Cy 3 $T_{tot} \approx 8.7$ hrs (PI: A. K. Inoue)
- We covered the z_{ph} range (9.0 – 9.8) with 4 ALMA tunings

Hashimoto+18 *Nature*

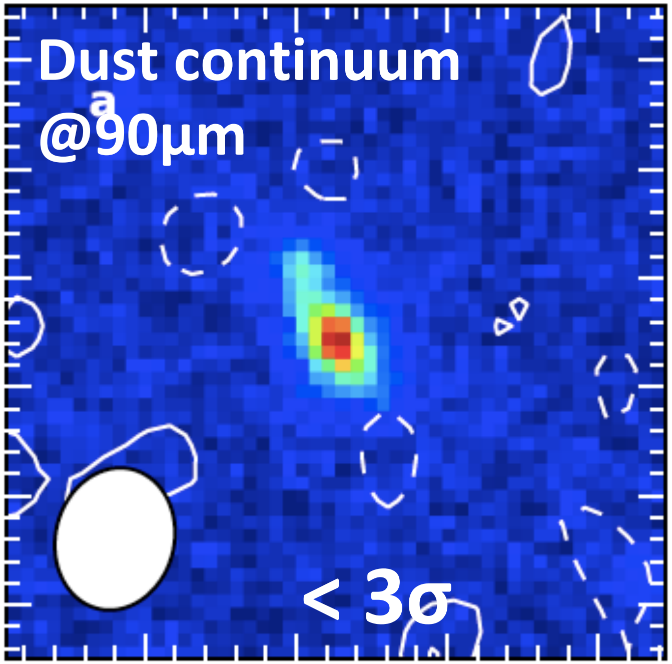




- $z_{OIII} = 9.1096 \pm 0.0006$
- SED (K. Mawatari) analyses show

age ≈ 300 Myr at $z = 9$ → $z_{form} \approx 15 \pm 2$

Dust continuum is undetected in JD1



$S_{\nu,90\mu m} < 5.3 \times (10/\mu_g)$ μJy/B (3σ)

MBB: $S_\nu \sim \nu^{3+\beta}/(\exp(h\nu/kT_{dust})-1)$

T_d (K)	β_d	L_{TIR} ($10^9\ L_\odot$)	M_d ($10^5\ M_\odot$)
30	1.5	$< 6.0 \times (10/\mu)$	$< 20.0 \times (10/\mu)$
60	1.5	$< 17.3 \times (10/\mu)$	$< 1.3 \times (10/\mu)$

$$L_\nu(\mathrm{dust}) = \frac{2h\nu^3}{c^2}\kappa_\nu(\beta)\frac{M_{\mathrm{dust}}}{e^{h\nu/k_b T_{\mathrm{dust}}}-1}$$

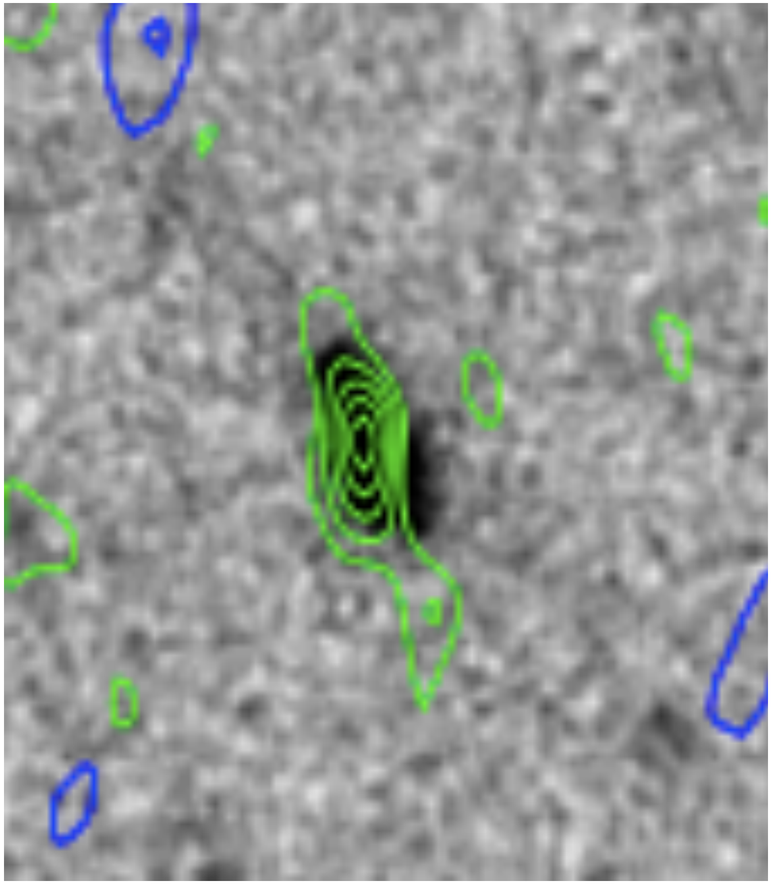
- $M_* \approx 1 \times 10^9 \times (10/\mu_g)\ M_\odot$ from SED-fit
- $\log(M_d\text{-to-}M_*) < -4$ to -3 (3σ) for T_d = 60 - 30 K (c.f., Popping+17)

  cf., $\log(M_d\text{-to-}M_*) \approx -4$ to -1 @ $M_* \approx 1 \times 10^9\ M_\odot$ at z = 0

➔ **Useful constraint for theoretical dust models** (e.g., Calura+17)

[CII] 158 is undetected in MACS1149-JD1

- Deep follow-up observations for [CII] 158 μm (PI: N. Laporte)
- Similar beam size as used in [OIII] 88 μm observations



green → [OIII] 88 μm
blue → [CII] 158 μm

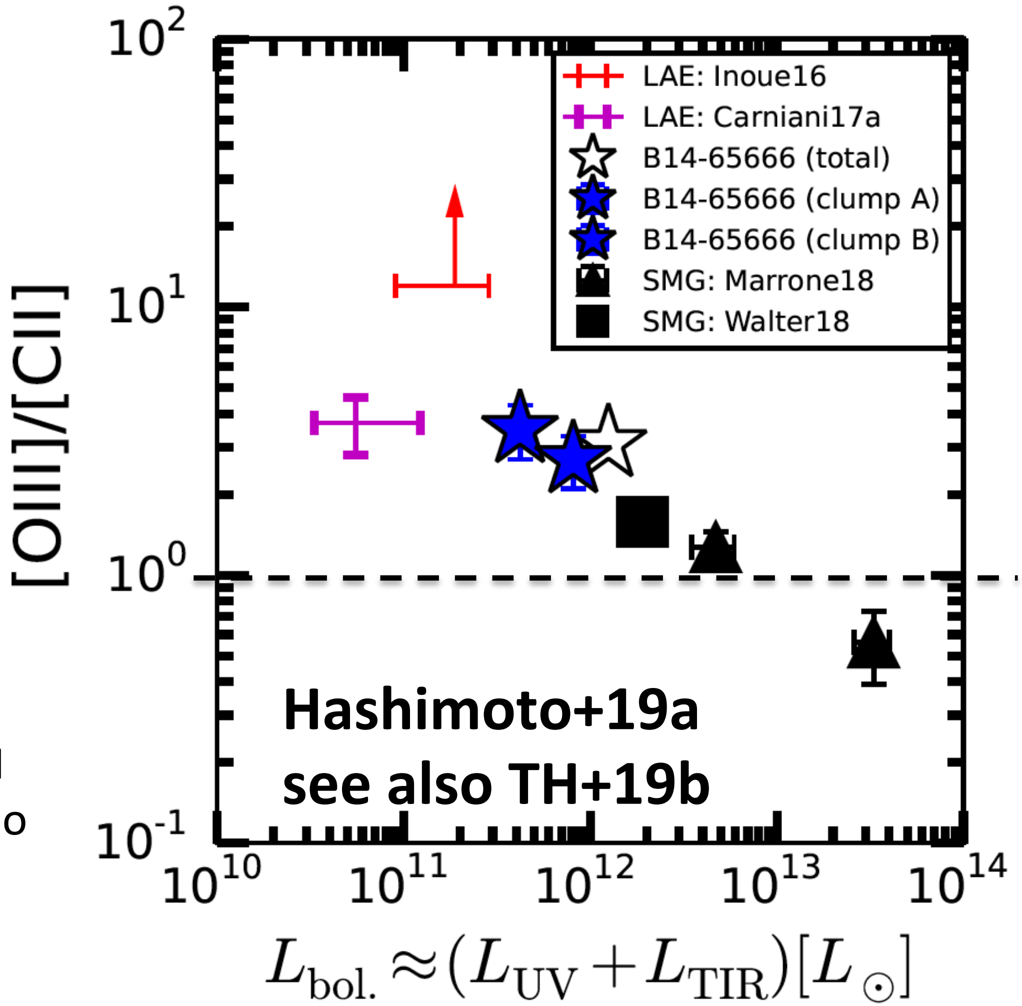
Laporte incl. TH+19

- L[OIII]/L[CII] > 18.5 (3σ; **the highest ratio to date: later discussion**)

Outline

- **Introduction**
  - Cosmic reionization
  - Galaxies in the epoch of reionization (EoR)
    - Spectroscopy
- **Rest-frame FIR properties at z > 7 with ALMA**
  - **Case study:**
    properties of a z = 9.1 [OIII] 88μm emitter
  - **Statistics:**
    High ratios of L[OIII] 88 μm/L[CII] 158 μm
    in high-z LAEs/LBGs
- **Some thoughts on AAT**

[OIII] 88/[CII] 158 luminosity ratio@z=6-9

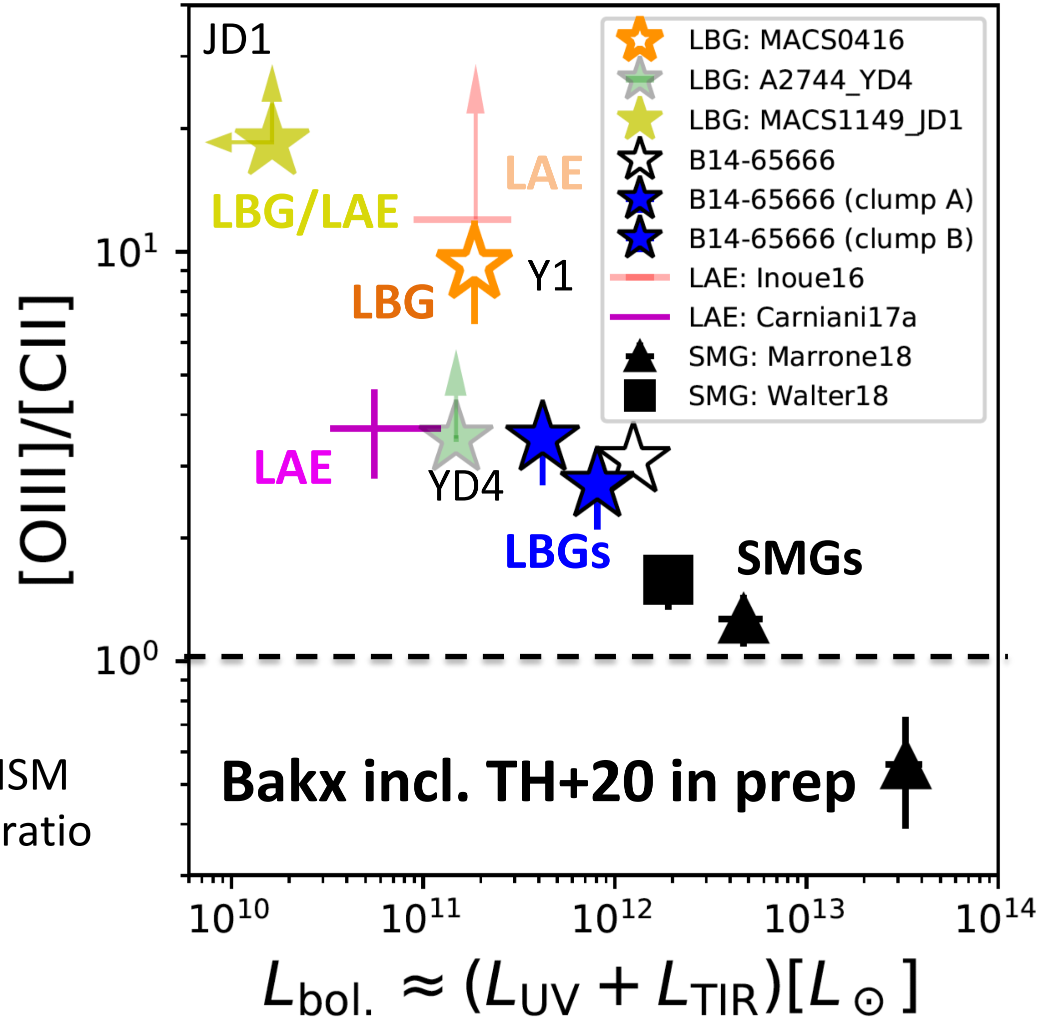


[OIII] 35 eV
[CII] 11 eV
highly-ionized ISM
has a line high ratio

For LAEs/LBGs:
Td=50 K β = 1.5
is assumed

- Anti-correlation between [OIII]/[CII] and $L_{\rm bol.}$

[OIII] 88/[CII] 158 luminosity ratio@z=6-9



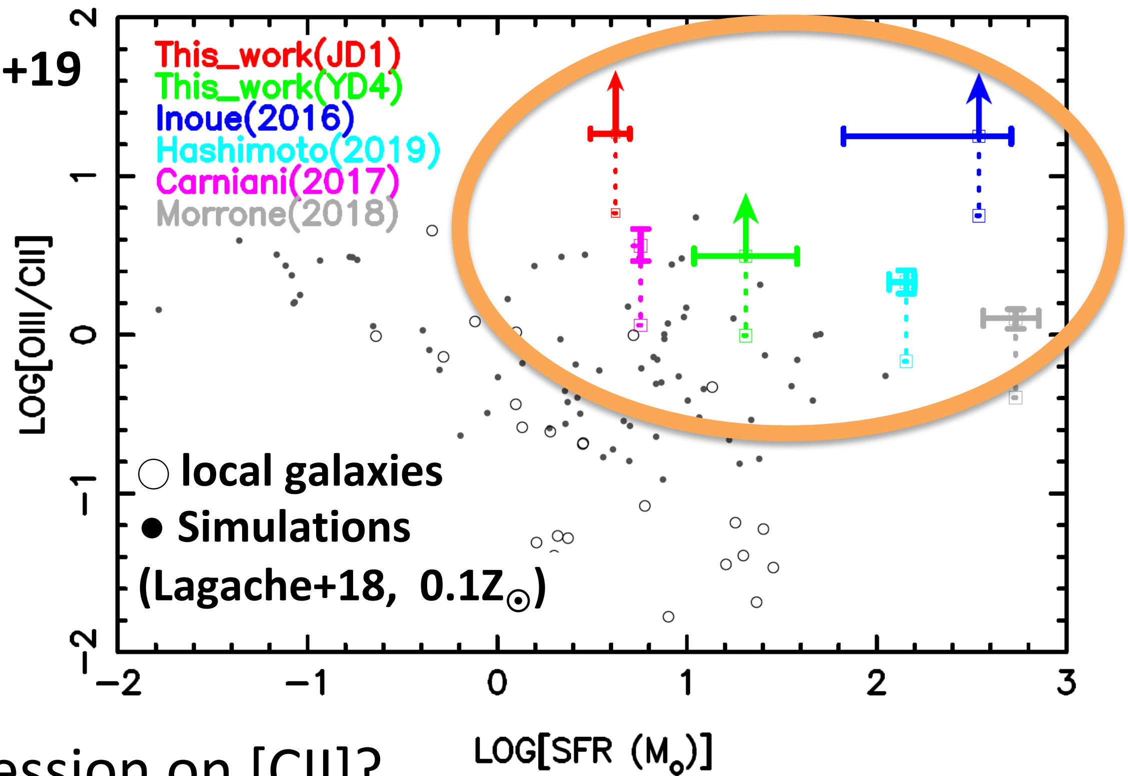
[OIII] 35 eV
[CII] 11 eV
highly-ionized ISM
has a line high ratio

For LAEs/LBGs:
Td=50 K β = 1.5
is assumed

- Anti-correlation between [OIII]/[CII] and $L_{\rm bol.}$

Ubiquitously high [OIII]/[CII] ratios at z > 6

Laporte incl. TH+19



- CMB supression on [CII]?
  - T_{CMB} > 20 K cf., [CII] T_{ex} ≈ 92 K (**dashed-line: insufficient**)

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-T_*/T_s}$$

- High-ionization parameter in the ISM? (Inoue+16, TH+19a)
  - [OIII] P_{ion} (35 eV) vs. [CII] P_{ion} (11 eV) → **LyC escape ??**
- Some clues on O/C? (need ionization correction)

→ **Detailed modeling will be performed** (see also Harikane+19)

→ **Initial results highlight the unusual ISM conditions in the EoR**

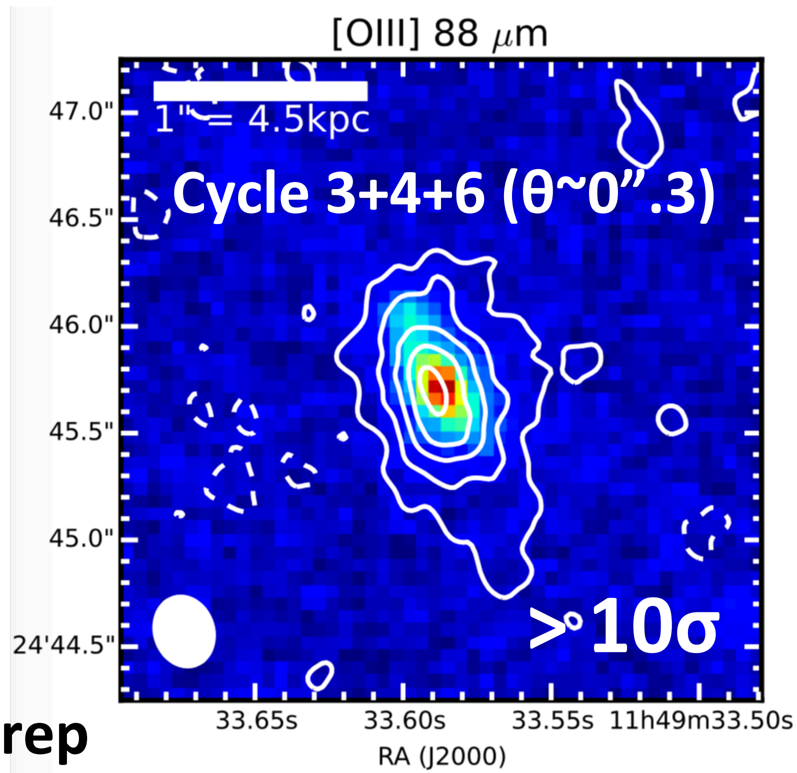
Ongoing Works of Our Team

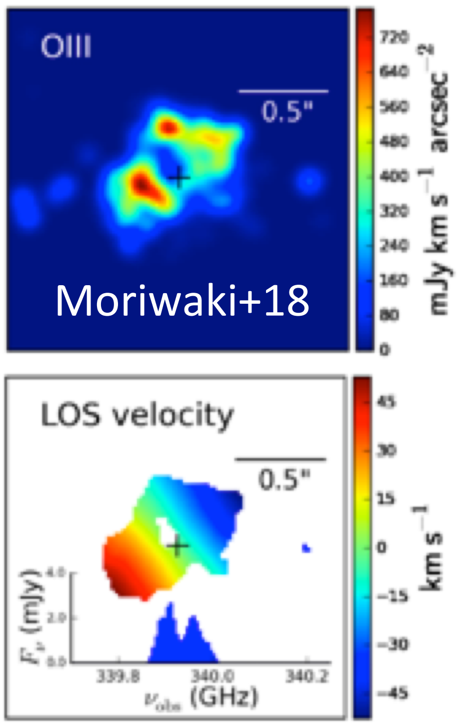
① Morpho-kinematic properties at z = 8 - 9

2 ALMA Cy6 projects with **"A"** (PIs: **Hashimoto**, Tamura)

→ A reference study for future *JWST* and ELTs science

Combined data have intrinsic resolution of ~ 500 x 400 pc^2





Tokuoka, TH+ in prep

Ongoing Works of Our Team

② [OIII] 88 μm for five z ~ 10 candidates

2 ALMA Cy7 projects with **"A"-33hrs** (PIs: **Hashimoto**, Tamura)

→ HST + Spitzer で得られる現在最高のサンプル

→ 2 supplementary VLT observations ongoing (PI: **Hashimoto**)
rest-frame UV lines

→ If confirmed, strong(est) *JWST* and ELT targets

③ Multiple line study for "Big Three Dragons" at z = 7.15

[OIII] 52, [NII] 122, CO(7-6) & CO(6-5) & [CI](2-1)

3 ALMA Cy7 projects **"B"** (PIs: **Matsuo**, Inoue, **Hashimoto**)

→ A comprehensive understanding of ISM in the EoR
critical density; nitrogen abundance, metallicity, gas properties

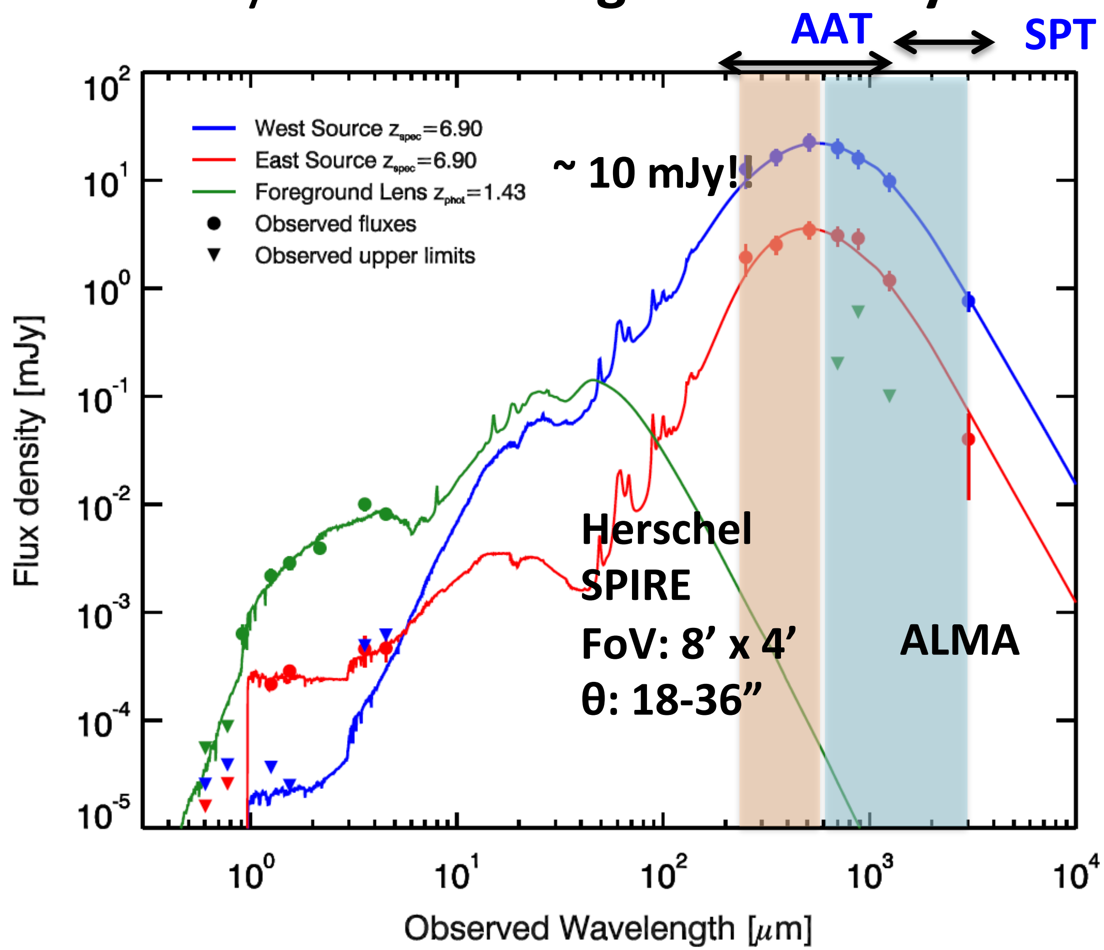
Outline

- **Introduction**
  - Cosmic reionization
  - Galaxies in the epoch of reionization (EoR)
    - Spectroscopy
- **Rest-frame FIR properties at z > 7 with ALMA**
  - **Case study:** properties of a z = 9.1 [OIII] 88μm emitter
  - **Statistics:** High ratios of L[OIII] 88 μm/L[CII] 158 μm in high-z LAEs/LBGs
- **Some thoughts on AAT**

Dust emission in the EoR

z = 6.90 lensed SMG(s)   Marrone+18 *Nature*

Originally discovered as a bright 2.0 and 1.4 mm source by the **2500 deg^2 SPT survey**

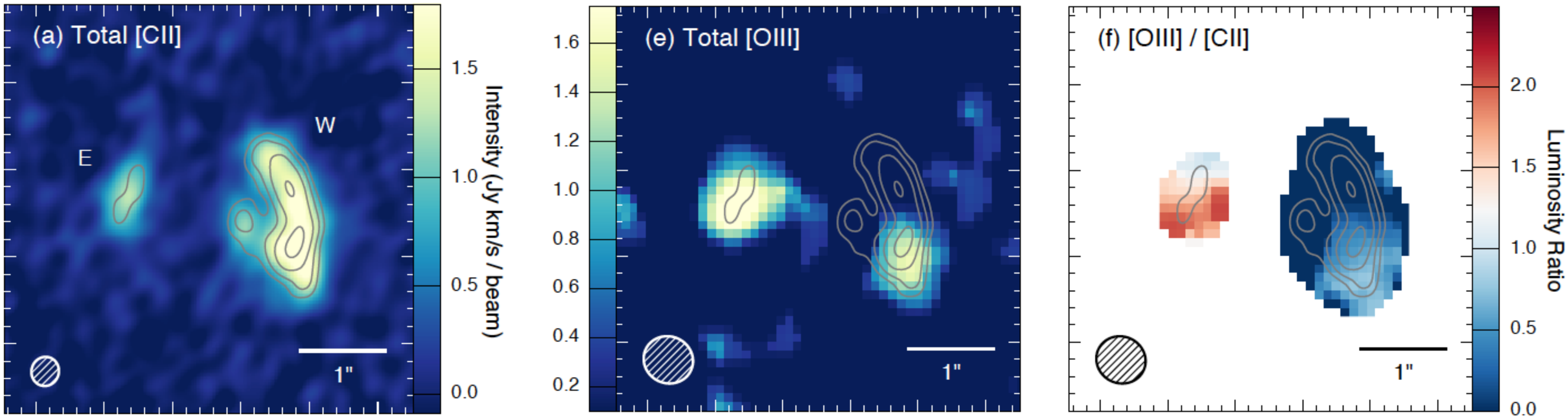


Combination of AAT & SPT can find such extremely dusty galaxies in the EoR
Toward a complete picture (UV+IR) of SFRD evolution (Madau&Dickinson 2014)

Dust emission in the EoR

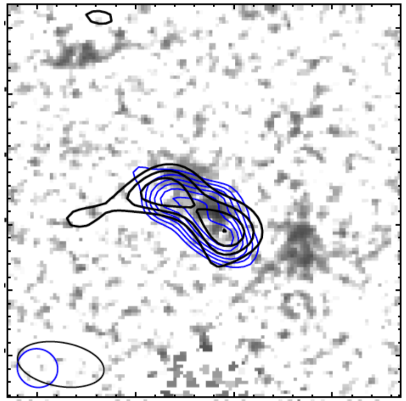
z = 6.90 lensed SMG(s)   Marrone+18 *Nature*

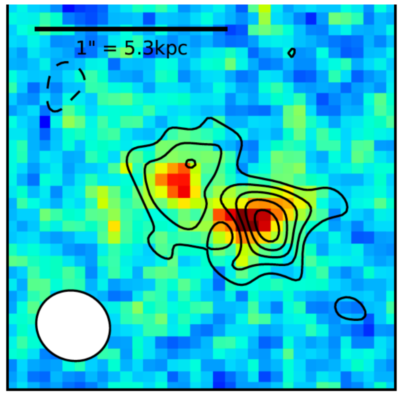
ALMA follow-up observations targeting **dust, [CII] 158, [OIII] 88**

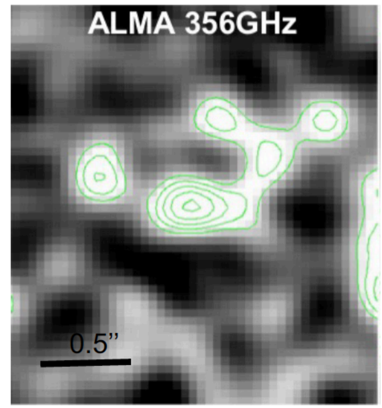


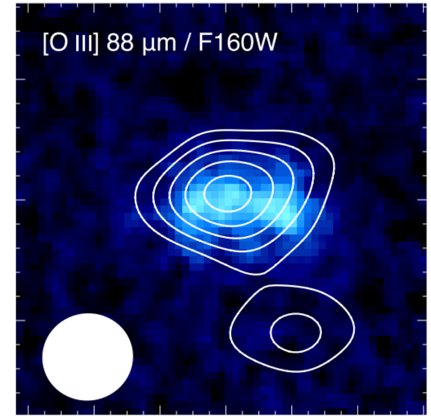
- E and W component has L_{IR} = (4.6 ± 1.2) and (33 ± 7) x **10^{12}** $L_{\odot}$
- E and W component has M_{dust} = (0.4± 0.2) and (2.5 ± 1.6) x **10^{9}** $M_{\odot}$
- [OIII]/[CII] luminosity ratio is ~ 2.0 and 0.5
- **[OIV] 26 μm with ATT or SPICA → AGN activity**

Dust emission in the EoR









- 4 (normal) star-forming galaxies (i.e., LBGs) with dust continuum beyond redshift z = 7 up to z = 8.3 all achieved with **ALMA**!

Object	redshift	λrest [μm]	Sν [μJy]	Ref.
A1689-zD1	~ 7.5	90 160	1670 ± 360 560 ± 100	**Inoue & Hashimoto+20 subm.** Watson+15 Nature
B14-65666	7.15	90 160	470 ± 128 130 ± 25	**Hashimoto+19a**
A2744_YD4	8.38	90 160	99 ± 23 < 11 (3σ)	Laporte+17 **Laporte incl. TH+19**
MACS0416-Y1	8.31	90 160	137 ± 26 < 18 (3σ)	**Tamura, Mawatari, TH+19** **Bakx, Tamura, incl. TH+20**

High T_d in high-z star-forming galaxies?

Object	redshift	Td	Ref.
A1689-zD1	~ 7.5	63 – 92 K	Watson+15 **Inoue & Hashimoto+20**
B14-65666	7.21	50 – 60 K	Bowler+18 **Hashimoto+19a**
A2744_YD4	8.38	60 – 100 K	Behrens+18
MACS0416-Y1	8.31	> 90 K	**Bakx, Tamura, incl. TH+20**

- A larger sample is crucial for a defitnive conclusion
- High T_d due to compact star-formation, strong UV radiation (e.g., Inoue&TH+20)
- Partly resolve the IRX-β_{UV} and dust mass budget problems (Faisst+17, Behrens+18)
- **High T_d leads to a dust peak at higher frequency (shorter wavelength) → strategy**

2020 - 2030年代に向けて

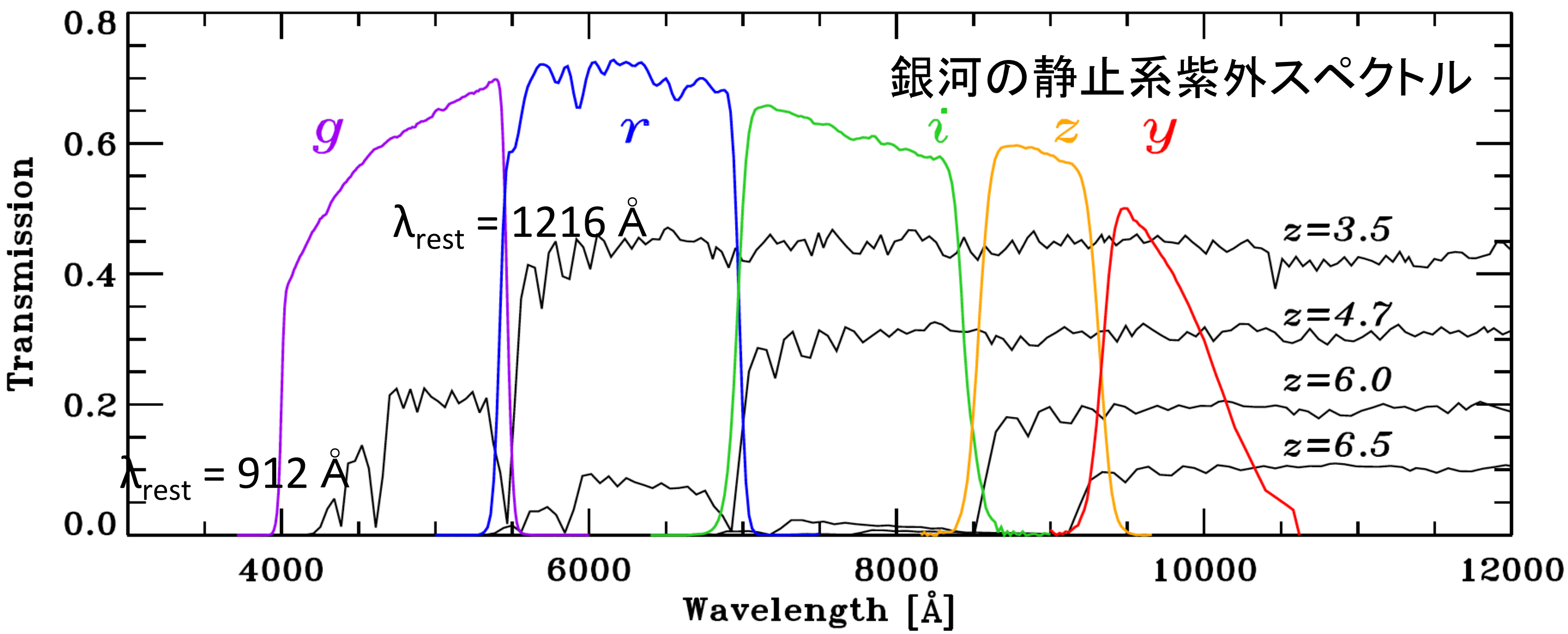
- 多波長間の連携が極めて重要
- Subaru/HSC (< 0.6 um) + WFIRST (mid 2020: 0.6-2um)
  2000平方度

NASA 2020 decadal survey

- WISH (Inoue, Kodama, Iwata+) 今後提案 2-5 um
  100平方度 27.5 mag (5σ)　cf., JWST は視野小
- AAT 200 um – 1.5mm ：広視野 (1平方度)
  同程度 (> 100 平方度) の探査領域が重要 (後述)

2020 - 2030年代に向けて

①例えば z = 15 の LBG (紫外選択天体) を考える
Lyman-break at (1+15) * 1216 Å ~ 20000 Å = 2 um



要は、2 um まで見えない天体
(深い未検出を確定するためデータは必要... HSC + WFIRST)

- **WISH (2-5 um) で 静止系可視**
  z = 15 LBGが選択可能になる

2020 - 2030年代に向けて

- 例えば z = 15 の LBG (紫外選択天体) を考える

- AAT (200 um – 1.5mm) で静止系中間赤外 – 遠赤外線 (13-94 um)

z = 15 LBG のダスト連続光ピーク 付近を抑えることが可能！
重要輝線: H2 分子輝線 17/28 um; [OIV] 26 um, [OIII] 52/88 um など
→ 個別で未検出でも多数スタックして平均像は得られる。

② 静止系 紫外-可視で暗く 赤外で明るい dusty SB @ z > 10
AAT (200 um– 1.5mm) + SPT (1.2 – 3.0mm)
同様に、静止系 紫外 – 可視 (観測波長 5 um程度まで)データは必須

多波長の2020-2030年代サーベイ予定を考慮しつつ、feasibility (感度、探査領域 etc.) が重要。
→ ALMA2 を通して詳細な分光フォローアップ