Spectroscopic census of ISM properties in high-z galaxies

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on behalf of the Large MOS survey WG of
K. Tadaki, M. Hayashi, T. Shibuya, and M. Akiyama

ULTIMATE-Subaru Science Workshop 2016@NAOJ on 16.06.2016

Answers (to be explained)

Q1: What do you think is the "KEY" science/observations for ULTIMATE in your research field?

--> Chemical evolution of galaxies probed by gas temperature.
Origin(s) of Lyα and Ly-Continuum photons escapes.

Q2: Which instrument (WFC/MOS/IFU) do you think is 1st priority for ULTIMATE?

--> MOS

Q3: Do you have good science cases to be done with GLAO+MOIRCS during the period of ~2020-2023?

--> We can substitute MOIRCS+AO and start to conduct follow-up observation if sensitivity and spectral resolution are comparable to those of MOSFIRE.

Q4: Which survey design sounds best for you (see *survey_design.pdf*)?

--> (D) ULTIMATE MOS spec. survey

Q7: For those who are interested in spectrographs (IFUs or MOS) : are you happy with our current specifications?

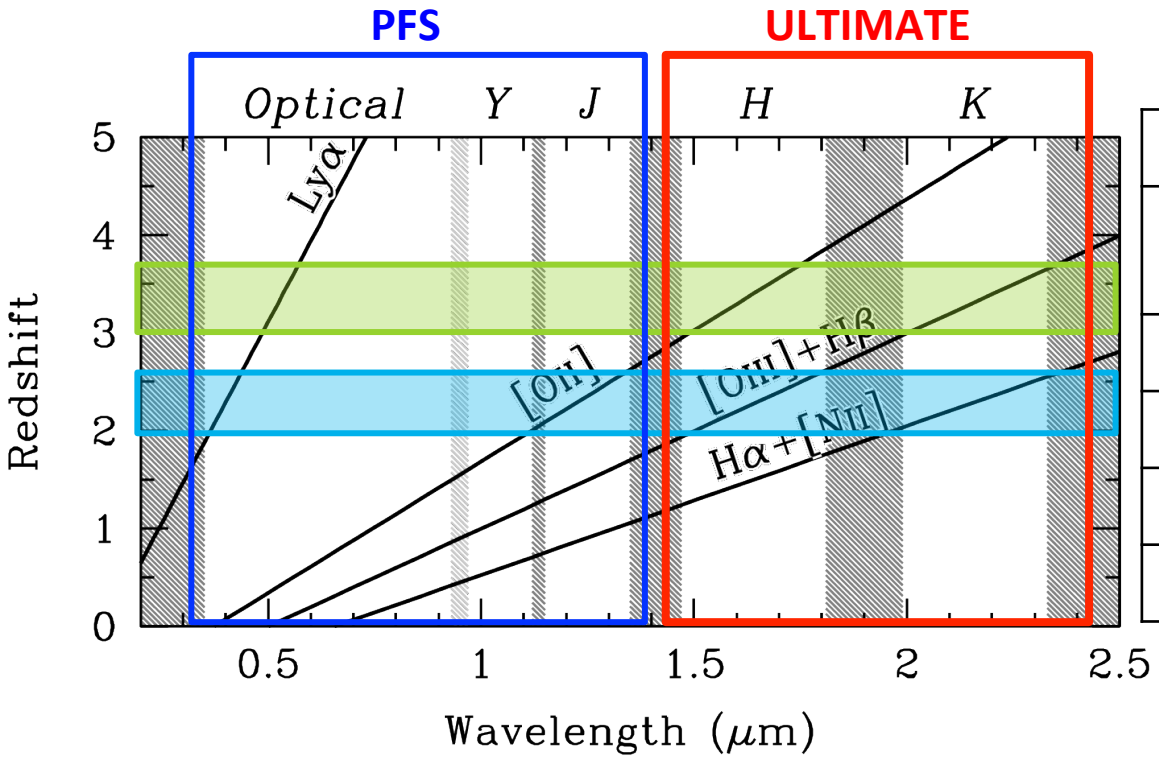
--> Yes. Improved sensitivity by GLAO, medium spectral resolution (R~3000), and high multiplicity (~100) would be nice.

MOS Survey Design

K+H spectroscopy for 1.8x10^4 z=2--5 galaxies over 3 deg^2 in 200 nights

+ LAEs and LBGs surveyed by HSC and identified by PFS
+ Mass-selected sample to probe massive galaxies

z=2.0-2.6 and z=3.0-3.7 are ***sweet spots***



Target	Redshift	N_{gal}
Mass-selected $\log M_{star}/M_{sun}>10.5$	2.0 – 2.6	15k
LBGs (w/ PFS)	2.0 – 2.6	4k
LBGs (w/ PFS)	3.0 – 3.7	2.5k
LBGs (w/ PFS)	4.4 – 5.2	0.5k
LAEs (w/ PFS)	2.2, 3.3, 4.9	3.2k

Proposed by K. Tadaki

Evolution of chemical enrichment in galaxies

z=0.1 Mass-Metallicity relation determined by 53,000 SDSS galaxies

+ star-formation quenching, *or* ***downsizing***
+ gas inflow, outflow
+ star-formation efficiency
+ gas fraction
+ … etc.?

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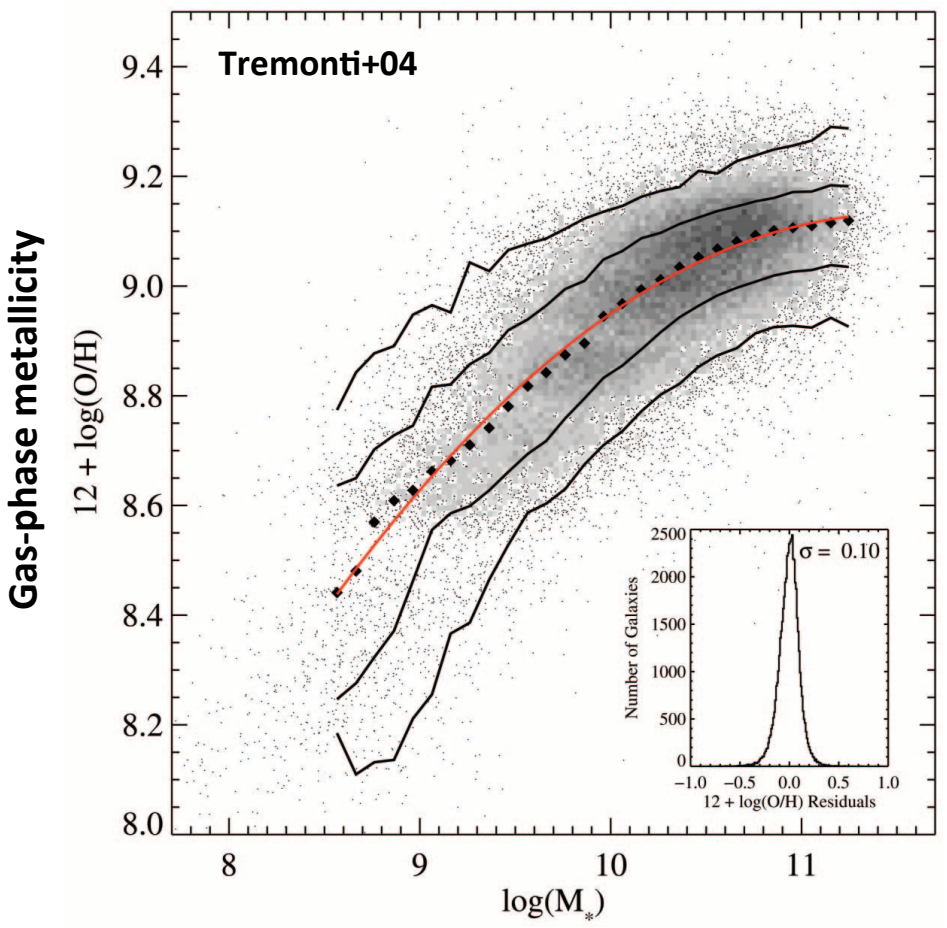
Higher-z MZR is needed
to constrain Physics
governing galaxy evolution



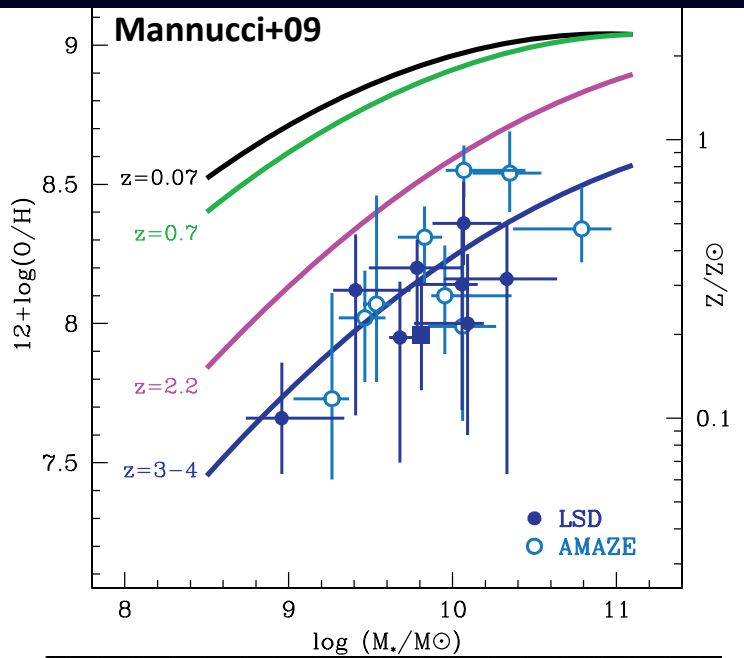
Evolution of chemical enrichment in galaxies

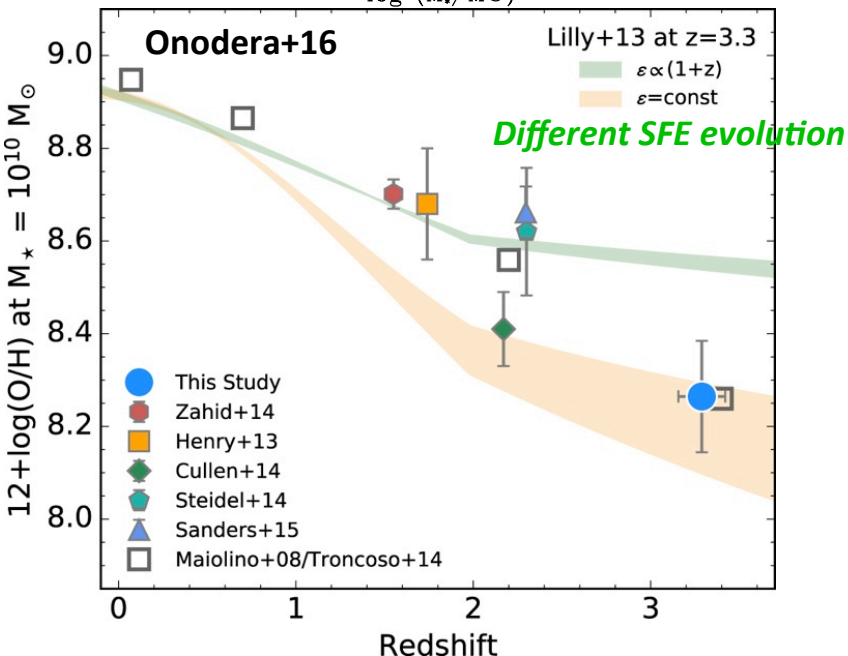
Higher-z galaxies are *observed to be* less chemically enriched

+ Actively star-forming galaxies are more dominant at high-z
  - Inflow of metal-poor gas ?
  - Outflow of metal-rich gas ?
+ More efficient star-formation?
+ … etc.?

For definitive conclusion, we need…

1) Larger samples
2) Accurate metallicity estimate





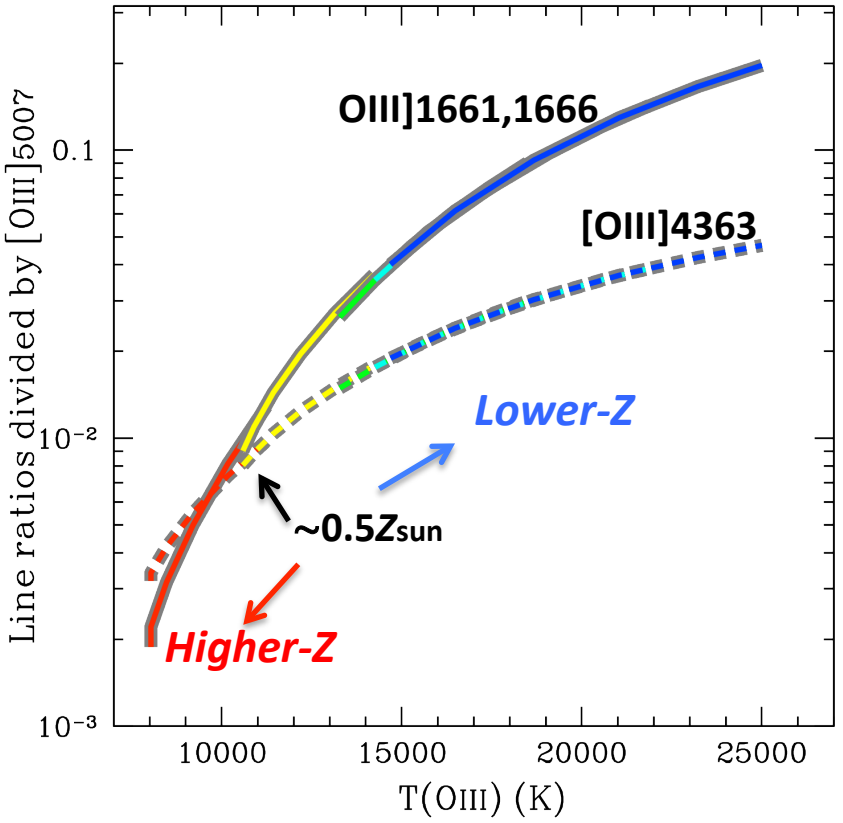
Metallicity estimate based on gas temperature

Accurate metallicity is provided by gas temperature

+ [OIII]4363/[OIII]5007
+ OIII]1661,1665/[OIII]5007

→ Limited by the faintness.
Only ~10 galaxies are reported at z>2 (e.g. Kojima+16)

→ Obtainable w/ PFS+ULTIMATE from several x100 z>2 galaxies
(cf. Kakazu+07)
up to Z<~0.5Zsun



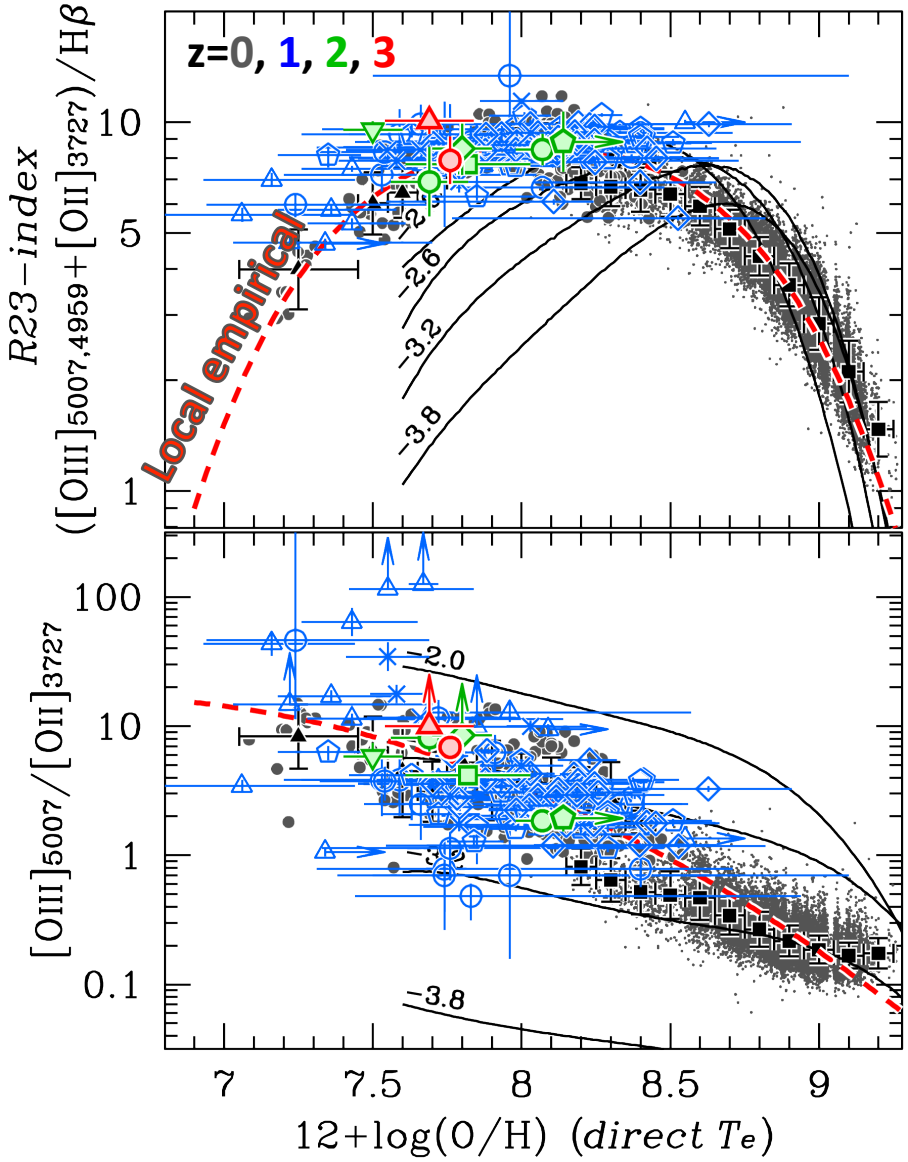
Improved metallicity diagnostics

Metallicity indicators of strong-line ratios need to be checked and re-calibrated at high-z

+ (Low-Z) Temperature method
+ (high-Z) Photoionization model

→ Complementary Z estimators
for galaxies w/o T_e measurement

→ Also enable us to examine…
- Evolution of ionization state
- Change of ionizing radiation field



Dust extinction correction

Balmer line ratios provide amounts of dust reddening of ionized gas

+ Hα/Hβ
+ Hγ/Hβ
+ Hδ/Hβ

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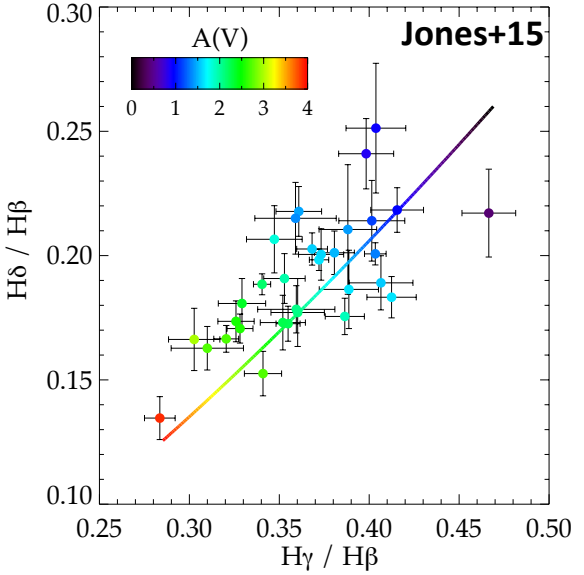
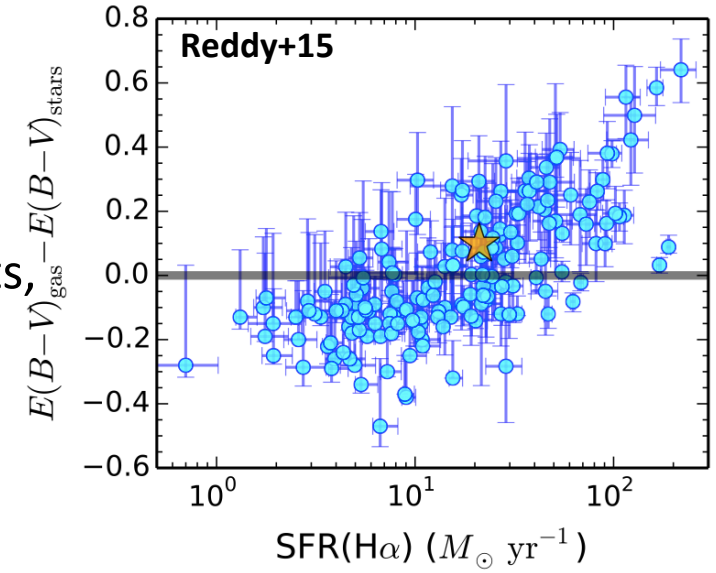
Absolute SFR
Accurate line ratios (PFS+ULTIMATE)



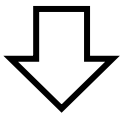
- Stellar absorption underneath Balmer lines can be directly evaluated in composite spectra
- For galaxies w/o Balmer decrement measurements, stellar reddening might be useful for nebular reddening estimate, but the $E(B\text{-}V)_{\rm nebular}$ vs. $E(B\text{-}V)_{\rm stellar}$ relation needs to be re-established (e.g. Reddy+15)



ISM properties probed with ULTIMATE

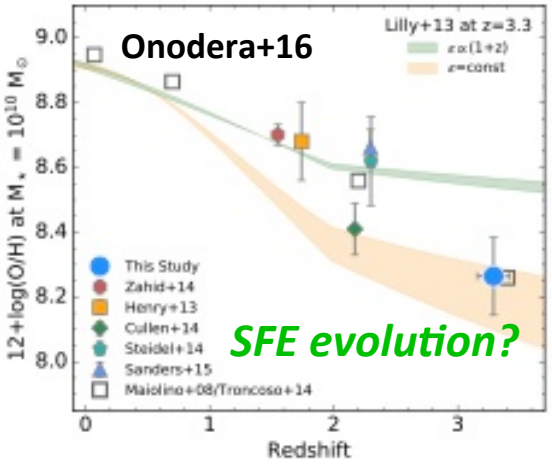
Reliable metallicity will be provided at z>2 as functions of …

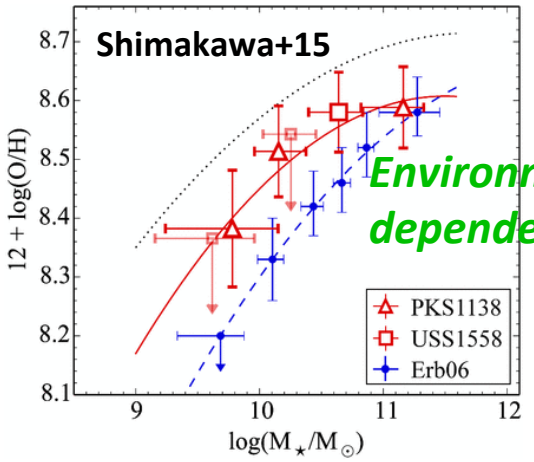
+ Stellar-mass
+ SFR
+ Environment
+ Ionization state
+ Gas fraction
+ Etc.

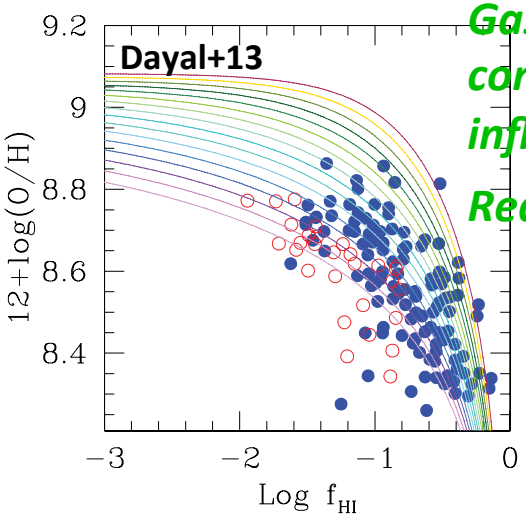


Conclusive picture of evolution of chemical enrichment in galaxies

--> Physics governing galaxy evolution





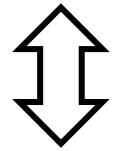


ISM properties at Epoch of Reionization

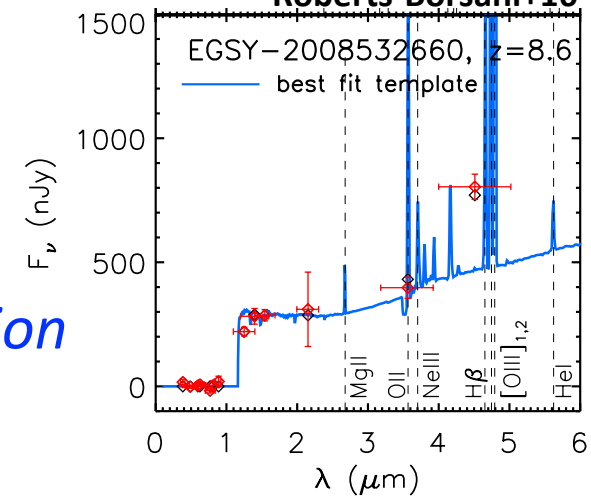
Some galaxies at EoR could have ISM properties very differently

+ Extremely strong [OIII]+Hβ (EW~1500A)
  - Hardness of ionizing radiation field?
  - Ionizing parameter?
  - Column density of HI gas?

JWST/NIRSpec *will provide direct identification*



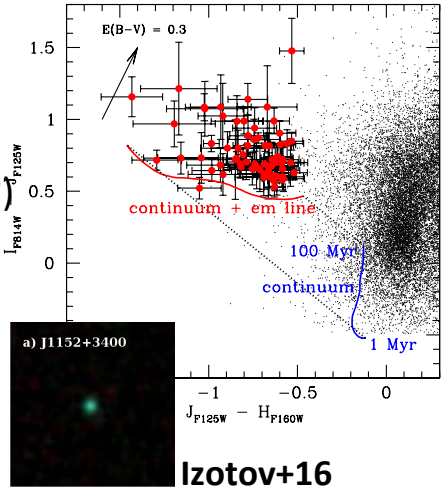
Roberts-Borsani+16



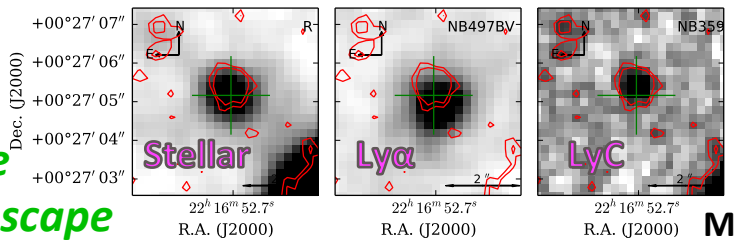
ULTIMATE *will enable us to fully examine the nature by observing lower-z(=2--4) counterparts*

+ High-z Green pea galaxies (van der Wel+11, Kakazu+07, searched by WFC?)
+ Galaxies showing highest [OIII]/[OII] (Nakajima&Ouchi+14, Izotov+16)
+ LyC leaking galaxies (Iwata+09, Micheva+15, searched by CHORUS)

van der Wel+11



Izotov+16



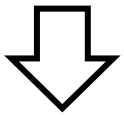
ULTIMATE can resolve clumps showing LyC escape

Micheva+15

Gas kinematics probed by FUV spectrum

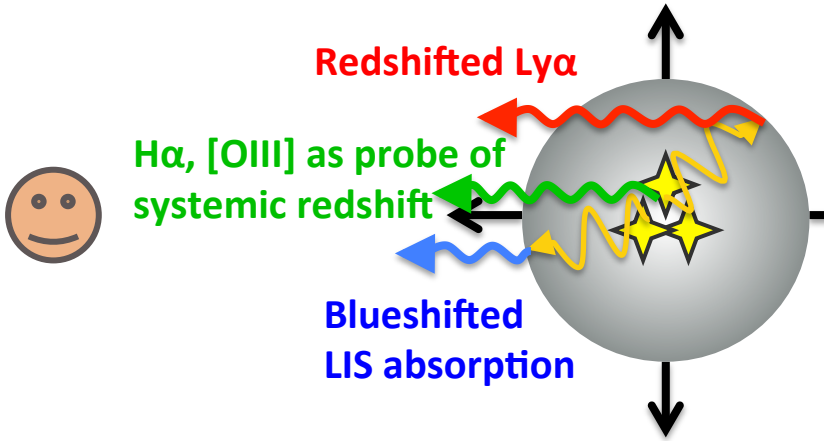
PFS+ULTIMATE will explore outflowing gas kinematics & properties

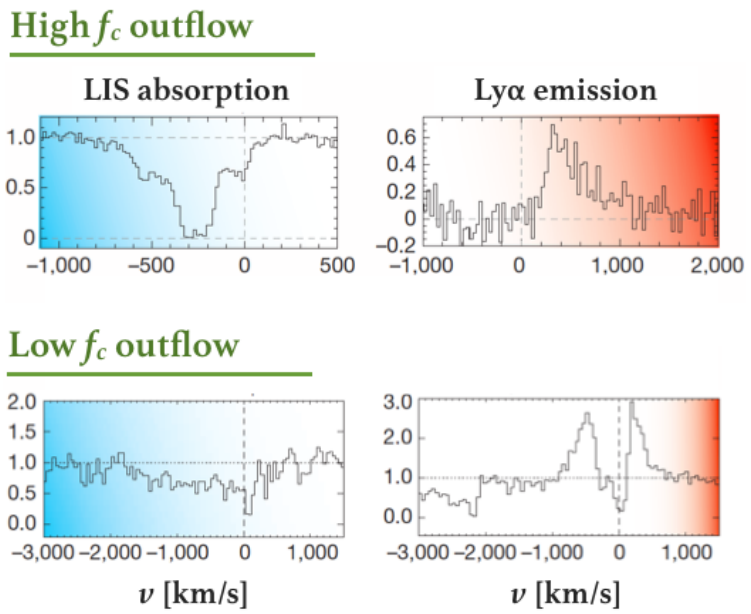
+ Lyα emission spectral shape
+ Low ionization interstellar lines (LIS) in absorption
+ Velocity offsets



+ Outflow velocity: $v_{Ly\alpha}$ and v_{LIS}
+ Neutral hydrogen column density: N(HI)
+ Gas covering fraction: fc

(e.g. Hashimoto+13,15, Shibuya+14, Erb+14, Jones+13)





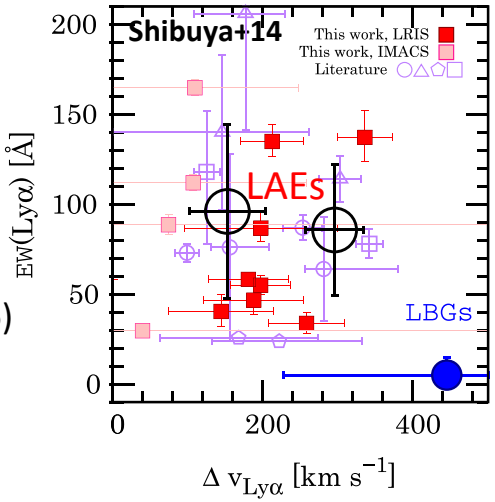
(c) T. Shibuya

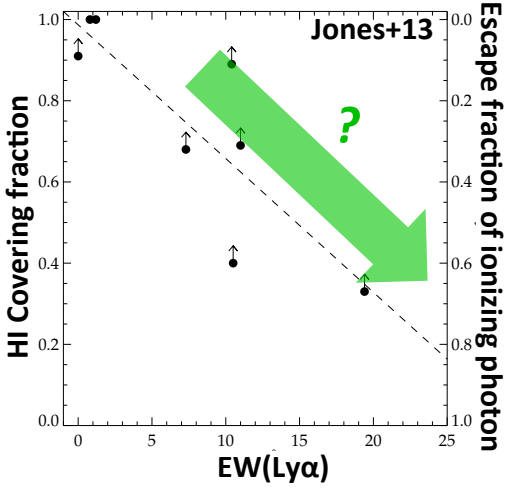
Origin(s) of Lyα and LyC photons escape

LAEs as Probe of Cosmic Reionization? Whose properties are …

PFS ULTIMATE

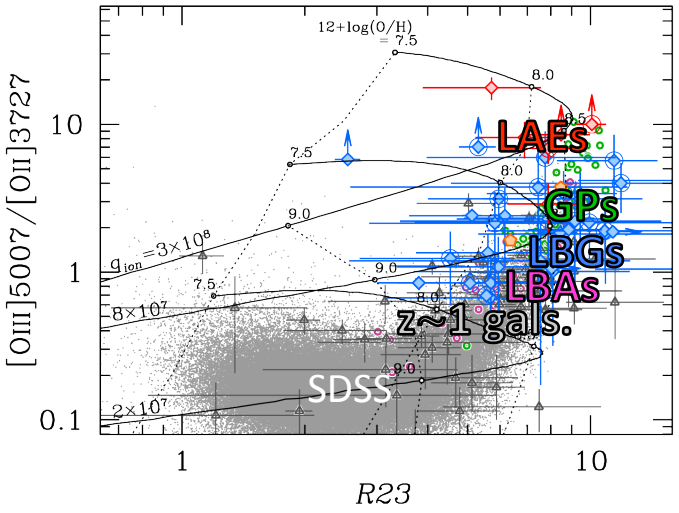
+ Less massive and actively SF *than LBGs*
  (e.g. Gawiser+06, Ono+10)
+ Small in size (Malhotra+12)
+ **Less chemically enriched ?**
  (Finkelstein+12, Nakajima+13)
+ **Highly ionized ?** (Nakajima&Ouchi 14, Erb+16)
+ **Less dusty ?** (Kusakabe+15)
+ **Comparable outflow velocity but Smaller *N*(HI) ?**
  (Hashimoto+13,15,Shibuya+14,Erb+14)
+ **Smaller covering fraction ?** (Jones+13), and **Higher escape fraction of ionizing photons ?**
  (Iwata+09, Nestor+13)





⇩ **Functions of f_{esc}(Lyα)**

Nakajima&Ouchi 2014



Interpret high-z JWST observations &
Understand role of galaxies at EoR
in supplying ionizing photons

Answers (summary)

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