Detectability of 21cm-signal during the Epoch of Reionization with 21cm-LAE cross-correlation

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based on
KH et al., 2016, arXiv: 1603.01961
Yoshiura, KH, et al., 2018 arXiv: 1709.04168
Inoue, KH et al. 2018, arXiv: 1801.00067

Sakura CLAW @ The Univ. of Tokyo, 26-30th March, 2018
Recombination  
z~1100

First Star Formation  
z~10-30

(First) galaxies & AGN formation?  
z<10

IGM is almost ionized.  
z~f6

• HI 21cm line: tracer of neutral hydrogen during the Epoch of Reionization (EoR)  
  => Provides us with fruitful information on the reionization process

• Difficulty: Intense foreground emission ~K >> EoR signal ~mK
21cm-LAE cross correlation

Map of HI 21cm signal

Distribution of LAEs

Why cross correlation?

21cm observation \( \delta_{21} = \delta_{21\text{sig}} + \delta_{21\text{noise}} + \delta_{21\text{FG}} \)

galaxy survey \( \delta_{\text{gal}} = \delta_{\text{gal\ sig}} + \delta_{\text{gal\ noise}} \)

\[ \langle \delta_{21} \delta_{\text{gal}} \rangle = \langle \delta_{21\text{sig}} \delta_{\text{gal\ sig}} \rangle + \cdots + \langle \delta_{21\text{FG}} \delta_{\text{gal\ sig}} \rangle + \langle \delta_{21\text{FG}} \delta_{\text{gal\ noise}} \rangle \]

\[ \sim 0 \]

- Estimate the detectability of 21cm - LAE cross power spectrum (CPS).
- Modeling reionization process and LAEs.
Reionization Simulation

Two-Step Approach:

1) High resolution cosmological Radiation Hydrodynamics (RHD) simulation (radiative transfer is consistently coupled with hydrodynamics) in a $(20\text{Mpc})^3$ box. (e.g., KH & Semelin, 2013, KH et al. 2016)

- Properties of galaxies (e.g., intrinsic ionizing photon emissivity, $\text{Ly}_\alpha$ Luminosity, escape fraction of ionizing photons as a function of halo mass).
- Small-scale clumping factor in the IGM

2) Large-scale Radiative Transfer simulation $(160\text{Mpc})$ with the models of galaxies and clumping factor. (e.g., Kubota et al. 2018, Yoshimura et al. 2018)

- Representative reionization history
- Spatial Distributions of HI.
4096^3 particles for N-body
\(M_{h,min} = 2.5 \times 10^7 M_{\text{sun}}\)
256^3 grids for RT
\(dx = 0.6 \text{Mpc}\)
Comparison: Simulations vs Observations

Constraint by QSO spectra

- Our simulation well reproduces the observations.
- ~factor 2 uncertainty in the ionizing photon emissivity is allowed to reproduce the observations.

What about LAEs?
Distribution of Observable Lyα Emitting Galaxies

Intrinsic LAEs at z=7.3

From RHD simulation

\[ L_{\alpha,\text{int}} \approx 10^{42} \left( \frac{M_h}{10^{10} M_\odot} \right)^{1.1} \text{[erg/s]}, \]
Distribution of Observable Lyα Emitting Galaxies

**Intrinsic LAEs at z=7.3**

**Obserbable LAEs at z=7.3**

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From RHD simulation

\[
L_{\alpha,\text{int}} \approx 10^{42} \left( \frac{M_h}{10^{10} M_\odot} \right)^{1.1} \text{[erg/s]},
\]

Lyα escape fraction : Parameter

\[
L_{\alpha,\text{obs}} = f_{\text{esc},\alpha} T_{\alpha,\text{IGM}} L_{\alpha,\text{int}}.
\]

Ray-tracing through the IGM

(Yajima, Sugimura, KH+, 2018)
Collaboration with a Subaru HSC project (SILVERRUSH) Inoue, KH, et al. 2018

- To reproduce observed Angular Correlation Function and Luminosity function, $M_{\text{halo}}$-dependent escape fraction ($\langle \tau \rangle \propto M_{\text{halo}}^{1/3}$) with a large scatter is favored.
- Ly$\alpha$ RT simulations (e.g., Yajima et al. 2014) show the similar trend.

**Modelling Ly$\alpha$ Emitting Galaxies**

**ACF (Obs data (red circles) from Ouchi et al. 2018)**

![ACF Plot](image)

**Ly$\alpha$ LF**

![Ly$\alpha$ LF Plot](image)
**Preparation for estimating the detectability of the CPS**

HI 21cm signal estimated from our simulation

\[
\delta T_b \approx 28 \times \frac{x_{\text{HI}} (1 + \delta)}{10} \left( \frac{1 + z}{10} \right)^{\frac{3}{2}} \frac{T_s - T_{\text{CMB}}}{T_s} \quad [\text{mK}]
\]

### HSC Deep:
- Total survey Area: 27 [deg\(^2\)] \(\sim 0.5\) \(h^{-3}\)Gpc\(^3\)
- Limiting Luminosity: \(4.1 \times 10^{42}\) erg/s \(\text{at } z=6.6\)
- Redshift error = 0.0007 w/ PFS
  = 0.1 w/o PFS

### SKA
- FoV: \(~25\) [deg\(^2\)]
- 670 antennae within 1000m
- 1000hrs observing time
Errors on the cross-power spectrum

based on Furlanetto&Lidz(2007)

Error on 21cm observation
\[ \delta P_{21}(k, \mu) = P_{21}(k, \mu) + \frac{T_{sys}^2}{B \tau_{int}} \frac{D^2 \Delta D}{n(k_\perp)} \left( \frac{\lambda^2}{Ae} \right)^2, \]
\[ \mu = \cos \theta: \text{angle between LOS and } k \]
\[ \text{sample variance + thermal noise } \sigma_N \]

Error on LAE survey
\[ \delta P_{gal}(k, \mu) = P_{gal}(k, \mu) + n_{gal}^{-1} \exp(k_\parallel \sigma_r^2), \]
\[ \text{sample variance + shot noise* } \text{z error } \sigma_g \]

Error on the spherically averaged cross-power spectrum
\[ 2[\delta P^2_{21,gal}(k, \mu)] = P^2_{21,gal}(k, \mu) + \delta P_{21}(k, \mu) \delta P_{gal}(k, \mu). \]
\[ \frac{1}{\delta P^2_{21,gal}(k)} = \sum \mu \Delta \mu \frac{\epsilon k^3 V_{sur}}{4\pi^2} \frac{1}{\delta P^2_{21,gal}(k, \mu)}, \]
\[ \delta P_{21,gal}(k) = \sigma_A(k) \propto \sqrt{P^2_{21,gal} + P_{21} P_{gal} + \sigma_g^2 P_{gal}} + \sigma_N P_{gal} + \sigma_N \sigma_g. \]
\[ \text{sample variance} \quad \text{detection limit} \]
Detectability of 21cm-LAE CPS w/o FG

\[ \sigma_A(k) \propto \sqrt{P_{21,gal}^2 + P_{21}P_{gal} + P_{21}\sigma_g + \sigma_N P_{gal} + \sigma_N\sigma_g} \]

variance = shaded
detection limit = curve

SKA1 (1000h) × HSC

z=6.6

red: simulated cross-power spectrum
black: sensitivity

- SKA × HSC Deep is expected to detect the signal at large scales (k<0.5 Mpc⁻¹)
Detectability of 21cm-LAE CPS w/o FG

\[ \sigma_A(k) \propto \sqrt{P_{21,gal}^2 + P_{21}P_{gal} + P_{21}\sigma_g + \sigma_N P_{gal} + \sigma_N \sigma_g} \]

- Variance = shaded
- Detection limit = curve

**SKA1 (1000h) × HSC**

\( z=6.6 \)

- Red: simulated cross-power spectrum
- Blue: sensitivity w/ PFS
- Black: sensitivity w/o PFS

Large scale \( \leq \) \( k [\text{Mpc}^{-1}] \) \( \Rightarrow \) Small scale

- SKA × HSC Deep is expected to detect the signal at large scales (\( k < 0.5 \text{ Mpc}^{-1} \))
- Spectroscopy by PFS enhances the detectability at small scales.
Detectability of 21cm-LAE CPS w/o FG

\[ \sigma_A(k) \propto \sqrt{P_{21,\text{gal}}^2 + P_{21}\sigma_g + \sigma_N^2 P_{\text{gal}} + \sigma_N \sigma_g}. \]

Expected errors on cross power spectrum (z=6.6)

**SKA1 (1000h) x HSC**

z=6.6

- **Red**: simulated cross-power spectrum
- **Blue**: sensitivity w/ PFS
- **Black**: sensitivity w/o PFS

large scale \(\leq \)

\[ k \leq 0.1 \text{ Mpc}^{-1} \]

**K. Kubota, S. Yoshiura, K. Takahashi, K. Hasegawa et al.**

- **SKA x HSC Deep** is expected to detect the signal at large scales (\(k<0.5 \text{ Mpc}^{-1}\))
- Spectroscopy by PFS enhances the detectability at small scales
- Behavior of the CPS at small scales is sensitive to the ionizing photon emissivities of LAEs (Kaneuji, KH; preliminary)
Impact of Foreground Emission

Point sources

MWA GLEAM catalogue
(Hurley-Walker+2017)
Modeled by J. Line

Diffuse emission

A parametric model of diffuse emission from our Galaxy
(Jelic et al 2008, Trott et al 2016)

• The contribution from foreground does not vanish.
• Foreground removal is still required for detecting the EoR 21cm signal, even in the case of CC analysis.
Summary

• A two-step approach (RHD + large-scale post-processing radiative transfer) to simulate the large-scale cosmic reionization process

• Modelling LAEs (Inoue, KH et al. 2018) $M_h$-dependent Lya escape fraction is favored

• PFS enhances the detectability of the 21cm-LAE CPS at low scales. (Kubota, KH et al. 2018)

• Many efforts for foreground removal is required even in the case of the CPS measurement. (Yoshiura, KH et al. 2018)