Understanding the epoch of reionization and the properties of the first galaxies represents an important goal for modern cosmology. The structure of reionization and hence the observed power spectrum of redshifted 21-cm fluctuations are known to be sensitive to the astrophysical properties of the galaxies that drove reionization. Thus, detailed measurements of the 21-cm power spectrum and its evolution could lead to measurements of the properties of early galaxies that are otherwise inaccessible.

In this talk, I will show predictions for the ionized structure during reionization and the 21-cm power spectrum based on detailed models of galaxy formation.
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Thus, detailed measurements of the 21-cm power spectrum and its evolution could lead to measurements of the properties of early galaxies that are otherwise inaccessible.
Making predictions for the ionized structure during reionization and the 21-cm power spectrum based on detailed models of galaxy formation.

Combined the GALFORM model implemented within the Millennium-II dark matter simulation, with a semi-numerical scheme.

Halo mass resolution ~ $10^8$ solar masses corresponding to the faint sources thought to dominate reionization.

Using these models we show that the details of supernovae and radiative feedback affect the structure and distribution of ionized regions, and hence the slope and amplitude of the 21-cm power spectrum.
Outline

Our method.
21-cm power spectrum predictions.
(Kim+ 2013a : 2013MNRAS.428.2467K)
cross-power spectrum predictions between galaxy and 21-cm observations.
(Jaehong Park, Poster #10)
21-cm power spectrum from escape fraction dependencies.
(Kim+ 2013b : 2013MNRAS.tmp.1574K)
Hierarchical galaxy formation model

GALFORM
Millennium-II simulation merger tree

+ 

Semi-numerical scheme
• Rapid exploration of the parameter space of galaxy formation physics.
• Large, statically useful samples.
• Wide range of properties, multi-wavebands.
• Well explain local and moderate redshift observations.
We combine the semi-analytic GALFORM model implemented within the Millennium-II dark matter simulation, with a semi-numerical scheme to describe the resulting ionization structure.

The M-II simulation enough to resolve the halo mass \( \sim 10^8 \) which is dominant ionization source at redshift higher than 6.
Dark matter simulation (M-II)

\[ N_{\text{HI}, \text{cell}} = n_{\text{HI}}(\Omega_{\text{DM}, \text{cell}} + 1)V_{\text{cell}}, \]

Over-density of neutral hydrogen follows the dark matter (computed based on the Millennium-II Simulation density field).

- \( n_{\text{HI}} \) is the mean comoving number density of hydrogen atoms.
- \( V_{\text{cell}} \) is the comoving volume of the cell.

256\(^3\) cells, side length 0.3906 Mpc/h and comoving volumes 0.0596 Mpc\(^3\)/h\(^3\).
\[ \dot{N}_{\text{Lyc},i}(t) = \int_{\nu_{\text{thresh}}}^{\infty} \frac{L_{\nu,i}(t)}{h\nu} \, d\nu, \]

\( L_{\nu,i} \) is the spectral energy distribution of galaxy \( i \)

\( h \nu_{\text{thresh}} = 13.6 \text{eV} \).

\[ \dot{N}_{\text{Lyc,cell}}(t) = \sum_{i=1}^{N_{\text{cell}}} \dot{N}_{\text{Lyc},i}(t), \]

The total Lyman luminosity continuum of \( N_{\text{cell}} \) galaxies within the cell expressed as the emission rate of ionizing photons.

\[ N_{\gamma,\text{cell}} = f_{\text{esc}} \int_{0}^{\tau_{z}} \dot{N}_{\text{Lyc,cell}}(t) \, dt, \]

escape fraction
Based on equation (5), individual cells can have \( Q_{\text{cell}} < 1 \) : may be ionized by photons from stars formed quiescently and in bursts. This procedure forms the position dependent ionization field.

To find the extent of ionized regions using a sequence of real-space top-hat filter of radius \( R \).

The brightness of blue : Intensity of HI
Variant models
The predictions of UV luminosity functions from the models together with observational data points at high redshifts.
The Bow06 model (solid lines in Fig. 1) agrees well with the Monte Carlo merger trees. Good agreement is found with numerical results of sources assigned within the halo field by applying a filtering technique. The predictions of HI intensity maps of Bow06 and Lagos model are nearly identical to the Millennium-II dark matter simulation merger trees. The ionization structure resulting from GALFORM galaxies generates an estimate of the ionization field based on a catalogue of sources assigned within the halo field. We assume the number of photons produced by galaxies in the cell that enter into small regions of volume (or cells). We begin by binning galaxies from the GALFORM model within the Millennium-II dark matter simulation.

### Table: Predictions of HI intensity maps

<table>
<thead>
<tr>
<th>Models</th>
<th>$V_{144}$ [kms$^{-1}$]</th>
<th>$V_{165}$ [kms$^{-1}$]</th>
<th>T</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow06</td>
<td>30</td>
<td>485</td>
<td>1</td>
<td>Bower et al. (2000), $V_{144}$ value change</td>
</tr>
<tr>
<td>Lagos</td>
<td>30</td>
<td>485</td>
<td>1</td>
<td>Lagos et al. (2012)</td>
</tr>
<tr>
<td>Bow06 (no suppression)</td>
<td>30</td>
<td>485</td>
<td>1</td>
<td>Bower et al. (2006), No SNe feedback</td>
</tr>
<tr>
<td>NOSN</td>
<td></td>
<td></td>
<td>4</td>
<td>Bower et al. (2006), No SNe feedback</td>
</tr>
<tr>
<td>NOSN (no suppression)</td>
<td></td>
<td></td>
<td>4</td>
<td>Bower et al. (2006), No SNe feedback and No radiative suppression</td>
</tr>
</tbody>
</table>

No SNe feedback and No radiative suppression

---

It is important to consider how well the predicted galaxy properties of high-redshift galaxies at different in mass resolution limit) to compare model predictions with observed data at low redshift. Previously, Lacey et al. (2011) used GALFORM with Monte Carlo merger trees (with no built-in feedback) to compare model predictions with observed properties of high-redshift galaxies at high-redshift galaxy luminosity function. The semi-numerical scheme is an analogue of sources assigned within the halo field by applying a filtering technique. Good agreement is found with numerical results of sources assigned within the halo field by applying a filtering technique. The predictions of HI intensity maps of Bow06 and Lagos model are nearly identical to the Millennium-II dark matter simulation merger trees. The ionization structure resulting from GALFORM galaxies generates an estimate of the ionization field based on a catalogue of sources assigned within the halo field. We assume the number of photons produced by galaxies in the cell that enter into small regions of volume (or cells). We begin by binning galaxies from the GALFORM model within the Millennium-II dark matter simulation.
Subtraction of Bow06 map from models’ maps

Kim+ 2013a
The SNe feedback impacts on the 21cm PS at EoR not only amplitude but also slope.

Kim+ 2013a
Prediction for upcoming observation.

The predicted estimation from MWA with 1000hrs integration time and 6MHz of bandpass. (500 tiles from Lidz et al. 2008)
The cross-power spectrum between 21cm emission and galaxies in hierarchical galaxy formation models

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School of Physics, University of Melbourne
ARC Centre of excellence for All-sky Astrophysics (CAASTRO)

1. Abstract

The correlation between 21cm fluctuations and galaxies is sensitive to the astrophysical properties of the galaxies that drive reionization. Thus, detailed measurements of the cross-power spectrum and its evolution could provide a powerful measurement both of the properties of early galaxies and the process of reionization. In this work, we study the evolution of the cross-power spectrum between 21cm emission and galaxies using a model which combines the hierarchical galaxy formation model GAVOFM and the semi-analytic schemes to describe the reionization structure. We find that the evolution of different feedback processes changes the predicted cross-power spectrum, predominantly because the size of ionized regions at fixed ionized fraction is significantly affected by the strength of supernova feedback. We calculate predicted observational uncertainties for the cross-correlation coefficient and the cross-correlation function based on the specifications of the Maunakea (Maunakea) combined with galaxy surveys. We find that the cross-power spectrum could be detected over several square degrees of galaxy survey with galaxy-redshift errors less than 0.1.
The new method combines a hierarchical galaxy formation model (based on Millennium-II merger trees) with semi-numerical scheme to predict redshifted 21cm power spectrum during the EoR.

We could see the SNe feedback effect imprinted on the 21cm power spectrum at EoR.

If SNe feedback is effective at suppressing star formation at high redshift galaxies, radiative feedback does not lead to self-regulation of the reionization process.
The escape fraction of ionizing photons from their host galaxies is one of the most important unknowns for the reionization history. Observational estimates show a broad range of escape fraction values from a few per cent in the local Universe to a few per cent or a few tens of per cent at redshift $z \sim 1-3$. (Hurwitz, Jelinsky & Dixon 1997; Bland-Hawthorn & Maloney 1999; Putman et al. 2003; Iman, Iwata & Deharveng 2006; Shapley et al. 2006; Chen, Prochaska & Gnedin 2007; Iman et al. 2007).

However, there are no observational constraints on the escape fraction during the epoch of reionization.

Theoretically, the escape fraction is predicted to span a very broad range from 0.01 to 1. (Ricotti & Shull 2000; Wood & Loeb 2000; Benson et al. 2002; Ciardi et al. 2003; Eftekhari et al. 2003; Volonteri et al. 2003; Wyithe & Loeb 2007; Wise & Cen 2009; Haines et al. 2011; Kuhlen & Faucher-Giguère 2012).

We assume several different models for $f_{\text{esc}}$. We model dependencies of the escape fraction with halo mass and redshift using

$$f_{\text{esc}} = A \times \left( \frac{1 + z}{z} \right)^{\alpha} \left( \log_{10}(M_{\text{halo}}/h^{-1} M_{\odot}) \right)^{\beta}$$

$$N_{\text{esc}}(t) = f_{\text{esc}} \int_{\text{mass}} L_{\text{UV}}(t)/h \text{d}v$$

<table>
<thead>
<tr>
<th>Model</th>
<th>$A$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 0</td>
<td>0.53748</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Model I</td>
<td>0.1498</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Model II</td>
<td>1.0791</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>Model III</td>
<td>0.3649</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Model IV</td>
<td>0.0966</td>
<td>0</td>
<td>-5</td>
</tr>
</tbody>
</table>
We force to \( f_{esc} = 0 \) when the value of Eq. 7 is negative and \( f_{esc} = 1 \) when the value greater than unity. We also consider a fiducial model with \( f_{esc} = \text{constant} \). We assume \( F_c \) to equal 0.5.
The slope and amplitude of the 21 cm power spectrum, is dependent on the variation of ionising photon escape fraction.

Redshift dependence

Halo mass dependence

Prediction for upcoming observation

Kim+ 2013b
The dominant astrophysical effect provided by SNe feedback strength in high redshift galaxies influence bigger than unknown escape fraction and its evolution.

Kim+ 2013b
We find that the influence of the unknown escape fraction and its evolution is smaller than the dominant astrophysical effect provided by SNe feedback strength in high redshift galaxies.
The new method combines a hierarchical galaxy formation model (based on Millennium-II merger trees) with semi-numerical scheme to predict redshifted 21cm power spectrum during the EoR.

We could see the SNe feedback effect imprinted on the 21cm power spectrum at EoR.

If SNe feedback is effective at suppressing star formation at high redshift galaxies, radiative feedback does not lead to self-regulation of the reionization process.

We find that the influence of the unknown escape fraction and its evolution is smaller than the dominant astrophysical effect provided by SNe feedback strength in high redshift galaxies.
Thank you!!