An introduction of 21cm cosmology

Hayato Shimabukuro (Yunnan University, SWIFAR)
Introduction of myself

• Born in 沖繩

• Ph.D from Nagoya university (2016)

• Postdoc at Tsinghua University (2018-2019)

• Postdoc at Paris observatory (2016-2018)
Research interests

• Cosmology at small scales with 21cm forest (Warm dark matter, axion dark matter and so on)  
  [Shimabukuro et al.(2014), Shimabukuro, Ichiki, Kadota (2019)]

• 21cm statistics (bispectrum, one point statistics)  
  [Shimabukuro et al.(2015), (2016), (2017a)]

• 21cm signal analysis with artificial neural network (ANN)  
  [Shimabukuro & Semelin (2017b), Shimabukuro & Mao in prep, Shimabukuro, Mao, Fialkov in prep]
**History of the Universe**

- **Big Bang**
- **Dark Ages**
- **Recombination**
- **Epoch of Reionization (EoR)**

**Past**

**Dark Ages** • • • No luminous object exists. (z>~30?)

**Cosmic Dawn** • • • First stars and galaxies form. (z~30?)

**Epoch of Reionization (EoR)** • • • UV photons by luminous objects ionize neutral IGM. (z~6-15?)

**Present**
**History of the Universe**

- **Big Bang**
- **Dark Ages**
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- **EoR**

**past**

- **Dark Ages** • • • No luminous object exists. (z>~30?)
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**present**
Dark Ages to Cosmic Dawn

- Pop III stars
- Black holes
- X-ray binaries
- Galaxies

SMBH

IGM

heated
ionized
What do we want to know?

- How do first generation objects (e.g., first stars, first galaxies, black holes) form and evolve?
- What is the environment of first galaxies?
- When did reionization start?
- What is source of reionization?
- How do ionised regions evolve?
- What EoR model is preferred?

...etc
**Epoch of Reionization**

**Pre-overlap**: HII regions grow in relative isolation.

**Overlap**: Once galaxies become common, HII regions are overlapped.

**Post-overlap**: Ionising of IGM advances sufficiently.

- **Blue**: Neutral IGM
- **Red**: HII region
- **Yellow**: Ionizing source
Cosmic Reionization
From $z=20$ to $z=6$

Neutral Fraction
1.000e+00
0.75
0.5
0.25
0.000e+00

160 Mpc

(C)Kenji Hasegawa (Nagoya University)
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Current constraint

Constraints on reionisation history obtained by combined observations.
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(Banados et al 2017)
We want to study IGM at EoR more directly (ionization structure, evolution etc...)!
**21cm line radiation**: Neutral hydrogen atom in IGM emits the radiation due to the hyperfine structure.

\[
\begin{align*}
\Delta E &= 5.9 \times 10^{-6}\text{eV} \\
\lambda &= 21\text{cm} \\
\nu &= 1.42\text{GHz}
\end{align*}
\]

- \(z=6\) → 1.5m or 202 MHz
- \(z=20\) → 4.4m or 68MHz

Radio wavelength.

We can map neutral hydrogen atom in the IGM by 21cm lines.

However...

*We have yet to observe 21cm signal at EoR and cosmic dawn!*
21cm signal

Brightness temperature

\[ \delta T_b = \frac{T_S - T_\gamma}{1 + z} (1 - \exp(\tau_\nu)) \]

\[ \sim 27 x_H (1 + \delta_m) \left( \frac{H}{dv_r/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_m h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \text{[mK]} \]

Global signal (sky averaged brightness temperature)

Global signal has characteristic peaks and troughs according to key epochs.
We can see how ionised regions are distributed by 21cm image.
Images by 21cm line

\( x_i = 0.5 \)

\( x_i = 0.8 \)

(Minimum) required specification for imaging

○~ a few arc-minutes resolution  ○~ a few degree FoV
The observation of 21cm images requires high spatial resolution

(Minimum) required specification for imaging

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Images by 21cm line

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(Minimum) required specification for imaging

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21cm power spectrum

We first aim to detect 21cm signal \textit{statistically}.

21cm power spectrum (PS) : \[
\langle \delta T_b (k) \delta T_b (k') \rangle = (2\pi)^3 \delta(k + k') P_{21}
\]

Pober et al (2014)
Statistical challenge

Cosmology

CMB map \rightarrow (angular) power spectrum \rightarrow cosmological parameter

21cm

21cm 3D map \rightarrow 21cm power spectrum \rightarrow astrophysical parameter

Based on Bayesian inference
(Greig et al. 2015, Park et al. 2018) Calibrate model by observational UV luminosity function
How do we detect 21cm signal?
The measurement by radio interferometer is based on **time delay** between antennae.

We actually measure

- "Visibility"
- Fourier transform
- "Brightness temperature"
Radio interferometer

The measurement by radio interferometer is based on **time delay** between antennae.

\[ \theta = \frac{\lambda}{D} \]

**Resolution**

**Sensitivity**

- (effective collecting area)
- (thermal noise)
Current observations

• **MWA** (Australia)
  • $z=6-11.4$
  • Resolution : 2 arcmin
  • Array diameter : $\sim 3$km
  • Effective collecting area : 3500 m$^2$

• **LOFAR** (Netherlands)
  • $z=7-12$
  • Resolution : 3 arcmin
  • Array diameter : $\sim 2$km (core)
  • Effective collecting area : 18000 m$^2$

• **PAPER** (South Africa, USA)
  • $z=7-12$
  • Resolution : 30 arcmin
  • Array diameter : $\sim 200$m
  • Effective collecting area : 1100 m$^2$
Current upper limits on 21cm PS

$k \sim 0.2\text{Mpc}^{-1}$

Pritchard’s talk
SKA

- **SKA** (Australia)
- $z=6-28$
- Resolution : $\sim 7$ arcsec
- Array diameter : $\sim 80\text{km}$
- Effective collecting area : $\sim 300'000 \text{ m}^2$

**High resolution**

**High sensitivity**

![Image of SKA antennas](image-url)
Challenging issues

The 21cm signal is buried under strong foreground!

Jelic et al 2008

Remove foreground? or Avoid (strong)foreground?

Some approaches have been discussed.
Summary

• The epoch from dark ages to epoch of reionization is one of the milestones in the Universe

• 21cm line signal is powerful tool to study EoR and beyond.

• Currently, some ongoing telescopes are working to detect 21cm signal.

• In 2020’s, more powerful radio interferometers such as SKA will start.