Cosmology with the Square Kilometre Array
(by SKA-Japan)

Daisuke YAMAUCHI

Research Center for the Early Universe,
The University of Tokyo,
On behalf of SKA-Japan Consortium (SKA-JP)
Cosmology SWG
SQUARE KILOMETRE ARRAY

- Open a new window for Astronomy
  - New frequency regime
  - Wide sky coverage
  - High angular resolution
  - High sensitivity

![Graph showing sensitivity vs. frequency for different arrays: SKA1-LOW, SKA1-MID, SKA2, LOFAR, and JVLA. The x-axis represents frequency (GHz) and the y-axis represents sensitivity (m^2/K).](image)

MID (ν=0.35-10GHz)  LOW (ν=0.05-0.35GHz)
SKA Phase 1
(2018 – 2023)

Phase 1:
130,000 antennas across 80km of Australia

Phase 2:
500,000 antennas across 200km of Australia (2025 – 2033)

Phase 1:
200 dishes across 150km of Southern Africa

Phase 2:
2,500 dishes across 3500km of Southern Africa (2025 – 2033)
Scientific goals of SKA

The SKA aims to solve some of the biggest questions.

◆ **Fundamental physics**: Gravity, Dark Energy, Cosmic Magnetism

◆ **Astrophysics**: Cosmic Dawn, First galaxies, galaxy assembly and evolution, +...

◆ **The unknowns**: transients + ...

![Cosmic Dawn](image1.png) ![Magnetism](image2.png) ![Galaxy & Transients](image3.png) ![Gravity](image4.png)
Science WG of global SKA

(Global) Science working group

- Epoch of Reionization
- Continuum
- Cosmology
- Cradle of life
- HI galaxy science
- Magnetism
- Pulsars
- Transients

Focus group

- Our galaxy, Spectral lines, VLBI

Cosmic Dawn
Magnetism
Galaxy & Transients
Gravity
SKA-Japan Consortium

Chair: Sugiyama Nagoya U

Vice Chair: Akahori* Kagoshima U
Takahashi* Kumamoto U

Advisors: Kobayashi NAOJ Honma NAOJ

Publicity: Nakanishi* Kagoshima U

Funding: Imai* Kagoshima U

Engineering WG: Aoki* Waseda U

Science WG: Ichiki* Nagoya

Software: Kurayama Teikyo
Feed: Ujihara NICT
Signal process: Nakanishi* Kagoshima U
Industry forum: Kumazawa Toyo corp.

High-z galaxies: Hirashita ASIAA
Cosmology: Yamauchi* U Tokyo
Reionization: Hasegawa* Nagoya U
Galaxy evolution: Takeuchi* Nagoya U

Pulsars: Takahashi* Kumamoto U
Astrometry: Imai* Kagoshima U
Interstellar medium: Tachihara* Nagoya U
Transients: Aoki* Waseda U
Magnetism: Machida Kyushu U

[187 members (Sep.2015)]

(*)global SKA SWG
SKA-Japan Science Book

- In Japanese (published; 316 pages)
  1. Introduction
  2. Reionization
  3. Cosmology
  4. Galaxy Evolution
  5. Pulsars
  6. Cosmic Magnetism
  7. Astrometry
  8. Interstellar Medium
  9. Transients
  10. Summary

- Now being translated in English

SKA-Japan Science Book

D. Yamauchi (Tokyo, Chair)
K. Ichiki (Nagoya)
K. Kohri (KEK, Sokendai)
Y. Oyama (ICRR)
T. Sekiguchi (Helsinki)
H. Shimabukuro (Kumamoto)
K. Takahashi (Kumamoto)
T. Takahashi (Saga)
S. Yokoyama (Rikkyo)
K. Yoshikawa (Tsukuba)
Plan

1. Introduction

2. Cosmology with the SKA
   : brief review

3. Cosmology with the SKA
   by SKA-JP Cosmology SWG

4. Summary
Plan

1. Introduction

2. Cosmology with the SKA: brief review

3. Cosmology with the SKA by SKA-JP Cosmology SWG

4. Summary
Hydrogen 21cm-line

- Hyperfine transition of neutral hydrogen (HI)
- Characteristic line emission with \( \lambda = 21 \text{ cm} \) (\( \nu = 1.4 \text{GHz} \))
- HI mainly lives inside galaxies (after the Universe has reionized)

Can be used as a (biased) tracer of the 3D structure of the Universe
Radio continuum survey

- Measure galaxy synchrotron radiation radio emissions, which is also treated as a tracer of the large-scale structure.
- In the SKA era, the sufficient number source density will be expected.

HI survey

- HI galaxy redshift survey
  - The redshifting of HI-line provides the redshift info of galaxies.
  - The 3D matter distributions can be reconstructed.

- HI intensity mapping survey [after CD/EoR]
  - A novel technique to prove the large-scale structure. [Chang+(2010)]
  - The detection of individual galaxies is not required.
  - The integrated HI intensity of several galaxies in one pixel is measured.

- HI intensity mapping survey [during CD/EoR]
  - Measure the large-scale distributions of the HI inside the IGM via the brightness temperature.
<table>
<thead>
<tr>
<th>Observables</th>
<th>Surveys</th>
<th>SKA Phase</th>
<th>Redshifts</th>
<th>Coverage (deg^2)</th>
<th>Galaxy number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HI 21cm line</strong></td>
<td><strong>HI galaxy redshift survey</strong></td>
<td>Phase-1</td>
<td>z&lt;0.8</td>
<td>5,000</td>
<td>~ 10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;2</td>
<td>30,000</td>
<td>~ 10^9</td>
</tr>
<tr>
<td><strong>HI 21cm line</strong></td>
<td><strong>HI intensity mapping</strong></td>
<td>Phase-1</td>
<td>z&lt;3</td>
<td>30,000</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;3.7</td>
<td>30,000</td>
<td>--</td>
</tr>
<tr>
<td><strong>synchrotron rad.</strong></td>
<td><strong>Radio continuum</strong></td>
<td>Phase-1</td>
<td>z&lt;6</td>
<td>30,000</td>
<td>~ 10^8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;6</td>
<td>30,000</td>
<td>~ 10^9</td>
</tr>
<tr>
<td><strong>synchrotron rad.</strong></td>
<td><strong>Weak lensing</strong></td>
<td>Phase-1</td>
<td>z&lt;3</td>
<td>5,000</td>
<td>3 [arcmin^-2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;6</td>
<td>30,000</td>
<td>10 [arcmin^-2]</td>
</tr>
<tr>
<td><strong>optical/IR</strong></td>
<td>e.g. Euclid</td>
<td></td>
<td>z&lt;2</td>
<td>15,000</td>
<td>~ 10^8</td>
</tr>
</tbody>
</table>

\[ \Delta v/\nu = 0.3 @ 0.8-1.7[GHz], \Delta \theta = 1 \ [\text{arcsec}], t_{\text{int}} = 10^4 \ [\text{hour}] \]
<table>
<thead>
<tr>
<th>Observables</th>
<th>Surveys</th>
<th>SKA Phase</th>
<th>Redshifts</th>
<th>Coverage (deg$^2$)</th>
<th>Galaxy number</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI 21cm line</td>
<td>HI galaxy redshift survey</td>
<td>Phase-1</td>
<td>z&lt;0.8</td>
<td>5,000</td>
<td>$\sim 10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;2</td>
<td>30,000</td>
<td>$\sim 10^9$</td>
</tr>
<tr>
<td>HI 21cm line</td>
<td>HI intensity mapping</td>
<td>Phase-1</td>
<td>z&lt;3</td>
<td>30,000</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;3.7</td>
<td>30,000</td>
<td>--</td>
</tr>
<tr>
<td>synchrotron rad.</td>
<td>Radio continuum</td>
<td>Phase-1</td>
<td>z&lt;6</td>
<td>30,000</td>
<td>$\sim 10^8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase-2</td>
<td>z&lt;6</td>
<td>30,000</td>
<td>$\sim 10^9$</td>
</tr>
<tr>
<td>synchrotron rad.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 [arcmin$^{-2}$]</td>
</tr>
<tr>
<td>synchrotron rad.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 [arcmin$^{-2}$]</td>
</tr>
<tr>
<td>optical/IR</td>
<td>e.g. Euclid</td>
<td></td>
<td>z&lt;2</td>
<td>15,000</td>
<td>$\sim 10^8$</td>
</tr>
</tbody>
</table>

Even phase-1 IM and RC surveys will cover the extremely large survey volume (available full sky out to very high-z)!

$\Delta v/v = 0.3 @ 0.8-1.7$[GHz], $\Delta \theta = 1$ [arcsec], $t_{int} = 10^4$ [hour]
<table>
<thead>
<tr>
<th>Observables</th>
<th>HI galaxy redshift survey</th>
<th>HI intensity mapping</th>
<th>Radio continuum</th>
<th>Weak lensing</th>
<th>optical/IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI 21cm line</td>
<td>Phase-2 z&lt;0.8 5,000 ~ 10^6</td>
<td>Phase-2 z&lt;3 30,000</td>
<td>Phase-2 z&lt;6 30,000</td>
<td>Phase-1 z&lt;3 5,000 3 [arcmin^-2]</td>
<td>Phase-2 z&lt;6 30,000</td>
</tr>
<tr>
<td>synchrotron rad.</td>
<td>Phase-2 z&lt;3.7 30,000</td>
<td>Phase-2 z&lt;6 30,000</td>
<td>Phase-2 z&lt;6 30,000</td>
<td>Phase-2 z&lt;6 30,000</td>
<td>Phase-2 z&lt;6 30,000</td>
</tr>
</tbody>
</table>

When the Phase-2 is constructed, the flux threshold will be drastically improved (~5μJy), providing the spectroscopic survey of 1 billion HI galaxies can be delivered.

\[ \Delta v/v = 0.3 \, @ \, 0.8-1.7[\text{GHz}], \, \Delta \theta = 1 \, [\text{arcsec}], \, t_{\text{int}} = 10^4 \, [\text{hour}] \]
The HI galaxy and IM surveys will provide very accurate measurements for BAO/RSD of the large scale structure in its both phases.
Dark Energy with the SKA

Constraints on dark energy EOS

\[ w = \frac{P}{\rho} = w_0 + w_a \frac{z}{1 + z} \]
Dark Energy with the SKA

The SKA1 IM survey will be able to provide competitive constraints with Euclid, and the SKA2 HI galaxy survey is expected to allow further improvements.
Plan

1. Introduction
2. Cosmology with the SKA: brief review
3. Cosmology with the SKA by SKA-JP Cosmology SWG
4. Summary
SKA-JP Cosmology SWG

Cosmological scientific challenges in which we have a deep interest.

- **Ultra-large scale cosmology with multitracer technique**
  
  D. Yamauchi, S. Yokoyama, K. Takahashi, M. Oguri
  
  ✓ Density perturbations fully remains within the linear regime.
  ✓ Baryonic feedback are sufficiently suppressed.
  ✓ Clustering analysis is limited due to cosmic variance.

- **Exploring the dark Universe with the 21-cm surveys**
  
  
  ✓ Redshifted HI 21cm-line → 21cm tomography
  ✓ In high-z era, nonlinear growth is less effective than that in later era.
  ✓ Poor understanding of the astrophysical process during EoR
SKA-JP Cosmology SWG

Cosmological scientific challenges in which we have a deep interest.

● Ultra-large scale cosmology with multitracer technique
  D. Yamauchi, S. Yokoyama, K. Takahashi, M. Oguri
  ✓ Density perturbations fully remains within the linear regime.
  ✓ Baryonic feedback are sufficiently suppressed.
  ✓ Clustering analysis is limited due to cosmic variance.

● Exploring the dark Universe with the 21-cm surveys
  ✓ Redshifted HI 21cm-line ➔ 21cm tomography
  ✓ In high-z era, nonlinear growth is less effective than that in later era.
  ✓ Poor understanding of the astrophysical process during EOR
A critical test of primordial Universe

- One of the most powerful tests of inflation

→ Primordial non-Gaussianity

= Possible departures from a purely Gaussian distribution of primordial density fluctuations

- Hint about a mechanism for generating primordial fluctuations
- More generally key to understanding the extreme high-energy physics
A Key Science with SKA1 and SKA2

List of highest priority SKA1 science

<table>
<thead>
<tr>
<th>Science Goal</th>
<th>SWG</th>
<th>Objective</th>
<th>SWG Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - I. Imaging</td>
<td>1/3</td>
</tr>
<tr>
<td>2</td>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - II. Power spectrum</td>
<td>2/3</td>
</tr>
<tr>
<td>4</td>
<td>Pulsars</td>
<td>Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>Pulsars</td>
<td>High precision timing for testing gravity and GW detection</td>
<td>1/3</td>
</tr>
<tr>
<td>13</td>
<td>HI</td>
<td>Resolved HI kinematics and morphology of <del>10^10 M_sol mass galaxies out to z</del>0.8</td>
<td>1/5</td>
</tr>
<tr>
<td>14</td>
<td>HI</td>
<td>High spatial resolution studies of the ISM in the nearby Universe</td>
<td>2/5</td>
</tr>
<tr>
<td>15</td>
<td>HI</td>
<td>Multi-resolution mapping studies of the ISM in our Galaxy</td>
<td>3/5</td>
</tr>
<tr>
<td>18</td>
<td>Transients</td>
<td>Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State</td>
<td>1/4</td>
</tr>
<tr>
<td>22</td>
<td>Cradle of Life</td>
<td>Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc</td>
<td>1/5</td>
</tr>
<tr>
<td>27</td>
<td>Magnetism</td>
<td>The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields</td>
<td>1/5</td>
</tr>
<tr>
<td>32</td>
<td>Cosmology</td>
<td>Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.</td>
<td>1/5</td>
</tr>
<tr>
<td>33</td>
<td>Cosmology</td>
<td>Angular correlation functions to probe non-Gaussianity and the matter dipole</td>
<td>2/5</td>
</tr>
<tr>
<td>37 + 38</td>
<td>Continuum</td>
<td>Star formation history of the Universe (SFHU) – I+II. Non-thermal &amp; Thermal processes</td>
<td>1+2/5</td>
</tr>
</tbody>
</table>

“Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales”
Nonlinear parameters: $f_{NL}, \tau_{NL}, g_{NL}, \ldots$

- Primordial bispectrum (3-pt. fn.)
  \[
  \langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle = (2\pi)^3 B_{\Phi}(k_1,k_2,k_3) \delta^3(k_1+k_2+k_3)
  \]
  (amplitude) $\times$ (shape dependent fn)
  $f_{NL}$

- Primordial trispectrum (4-pt. fn.)
  \[
  \langle \Phi(k_1)\Phi(k_2)\Phi(k_3)\Phi(k_4) \rangle = (2\pi)^3 T_{\Phi}(k_1,k_2,k_3) \delta^3(k_1+k_2+k_3+k_4)
  \]
  (amplitude) $\times$ (shape dependent fn)
  $\tau_{NL}, g_{NL}$
PNG consistency relation

All inflationary models predict that (if $f_{NL} \neq 0$) the trispectrum must necessarily exist with

$$\tau_{NL} \geq ((6/5)f_{NL})^2$$

[Suyama+Yamaguchi (2010)]

The confirmation of the inequality would indicate the presence of complicated dynamics in the primordial Universe.

It should be the target in future experiments!
PNG in large-scale structure

- PNG induces the scale dependent-bias such that the effect dominates at very large scales:

\[ P_{\text{gal}} = [b_L(M,z) + f_{NL} \beta_f(M,z)/k^2 D_+(z)]^2 P_\delta \]

Galaxy surveys can effectively constrain PNG to the level comparable to CMB.

[Ferremacho+ (2014)]
Multitracer technique

- The availability of multiple tracers with the different biases allows significantly improved statistical error in the measurement of ratio of biases.

\[ \sigma(\ln P_{gal}) = \text{const.} \quad (N_{tot} \to \infty) \]

Limited due to CV!

\[ \sigma(b_h/b_l) \sim (N_l^{-1} + N_h^{-1})^{1/2} \quad (N_l, N_h \to \infty) \]

There is no fundamental limit!
Single-source case: \( \tau_{NL} = ((6/5)f_{NL})^2 \)

The constraints of \( \sigma(f_{NL}) = O(1) \) can be obtained even with a single survey. Combining Euclid and SKA, even stronger constraints of \( \sigma(f_{NL}) = O(0.1) \) can be obtained.

\[ \text{Euclid: photometric survey} \]
\[ \text{SKA: radio continuum survey} \]
Complementary information from SKA and Euclid helps to break the parameter degeneracy between PNG.

$\tau_{NL}$

Euclid: photometric survey
SKA: radio continuum survey

$g_{NL}$

SKA: $l_{min}=2$ (solid), $l_{min}=3$ (dashed)
Accessible region: \( f_{NL}/\sigma(f_{NL}) > 1 \) \& \( \tau_{NL}/\sigma(\tau_{NL}) > 1 \)
Accessible region: $f_{NL}/\sigma(f_{NL}) > 1 \& \tau_{NL}/\sigma(\tau_{NL}) > 1$

$\left(f_{NL}, \tau_{NL}\right) \sim (0.9, 8)$. 
Summary

- The SKA will yield transformational science across a wide range of cosmology in the next decade.

- Other topics that is of great interests for SKA-JP:
  - Precise measurement of primordial fluctuations [Kohri+Oyama+Sekiguchi+T.Takahashi (2013)]
  - Constraint properties of neutrino; \( \Sigma_{\text{m}_\nu} \), its hierarchy [Oyama+Kohri+Hazumi (2015), Oyama+Shimizu+Kohri (2013)]
  - Weak lensing: Synergy between SKA and CMB [Namikawa+DY+Sherwin+Nagata (2015), Saga+DY+Ichiki(2015)]

- SKA-Japan Science Book (in English) will appear soon.

Thank you!