The Dark Ages, Cosmic Dawn, and Epoch of Reionization

With the Square Kilometre Array

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on behalf of the SKA CD/EoR SWG

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Outline

• Why study the first $10^9$ years of the Universe?

• Current (non-HI) constraints on the Epoch of Reionization

• HI 21-cm emission through Cosmic Time

• The present: Current interferometric 21-cm experiments

• The future: Beyond current pathfinders: SKA 1 & 2 - low

see talks in the coming two sessions.
CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs.

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving “movie” of baryonic and DM structure formation at $t_{\text{univ}}<10^9$ years.
Visualization of the progress of reionization in a 1 Gpc/h volume. Ionized regions are blue and translucent, ionization fronts are red and white, and neutral regions are dark and opaque. A random sampling of 5 per cent (about 40,000) of all the halos at \( z = 0 \) are shown in yellow. Reionization is still quite inhomogeneous on these large scales, with large regions ionizing long before others.

Alvarez et al. 2009
Why and How Study the Universe’s First Billion Years?

Dark Ages
- DM power-spectrum evolution
- DM annihilation physics
- Baryonic Bulk Flows
- Physics of Gravity/GR

Cosmic Dawn
- Appearance of first stars (PopIII?)
- Ly-\(\alpha\) radiation field
- Impact of Baryonic Bulk Flows
- First X-ray heating sources

Reionization
- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Emergence of the visible universe

Space/Moon based Interferometers
- 2030+
- e.g. SKA/ELT/JWST
- ~2020

Present day Telescopes
- 2014
What do we know about the 1st Gyr of the Universe?

Current Observational Constraints on the Epoch of Reionization
High-z Quasars
Gunn-Peterson Troughs

Universe could be 10% neutral at z=7 and less than a few % neutral at z<6.5 (SDSS; Fan et al.)

Follow-up photometry of ULAS J1120+0641:
$F_{\lambda,i} = (0.1 \pm 0.4) \times 10^{-17}$ W m$^{-2}$ µm$^{-1}$; $i_{AB} \geq 25$
$F_{\lambda,z} = (0.6 \pm 0.2) \times 10^{-17}$ W m$^{-2}$ µm$^{-1}$; $z_{AB} = 24$
$F_{\lambda,Y} = (8.1 \pm 0.4) \times 10^{-17}$ W m$^{-2}$ µm$^{-1}$; $Y_{AB} = 20.3$
$F_{\lambda,J} = (6.0 \pm 0.4) \times 10^{-17}$ W m$^{-2}$ µm$^{-1}$; $J_{AB} = 20.2$

Mortlock et al. 2011
High-z Quasars
Gunn-Peterson Troughs

Universe could be 10% neutral at z=7 and less than a few % neutral at z<6.5 (SDSS; Fan et al.)
High-z GRBs

GRBs are tracers of massive-star formation. High-z GRBs are close to where the bulk of reionization seems to occur and a tracer of the high-mass SF rate.

Tanvir et al. 2009
IGM temperature

The IGM temperature around a QSO at $z=6$, extrapolated back allows a limit to be set on when EoR occurred.

This observation implies $z_{\text{EoR}} < 11$ (95% CL)
CMB Scattering Optical Depth

Re-scattering of CMB photons during and after reionization added to the polarization spectrum at large angular scales.

The scattering optical depth sets a limit on the EoR.

WMAP-7
Planck, w/o using polarization information yet, finds $\tau \sim 0.09$ and $z_{\text{re}} \sim 10$, consistent with WMAP, but slightly higher; rumors go that polarization data actually lowers $\tau \sim 0.075$.

This suggest that reionization is only halfway at $z < 10$.

$$\tau = 0.089 \pm 0.032 \quad (68\%; \text{Planck+lensing}).$$

Planck Collaboration, 2013 [XVI]
High-z Galaxies

Dropout techniques are finding galaxies to $z \sim 12$ [i.e. 1.4$\mu$m drop-outs].
High-z Galaxies

These observations seem to suggest a dramatic increase in the SFRD at $z<10$ consistent with CMB optical depth that suggest EoR at $z<10$.

Oesch et al. 2013

Break in the SFR density at $z>8$?

Rapid build-up of galaxies between $z \sim 10$ and $z \sim 8$. 
NIR Backgrounds

The current NIR background fluctuations can be explained by low-z galaxies and inter-halo stars, so current NIR limits on the EoR/CD are still weak.

Cooray et al. 2012
The unresolved soft X-ray background sets limits on the number of X-ray photons that could have been produced at different redshifts (e.g. during the CD/EoR.)

Hard spectra from HMXRB and e.g. DM annihilation can produce only $\sim0.1$ ionizing photon per HI atom at $z=10$ in order not to violate the observed limit.
Summary of Current Constraints on the EoR

• Scattering optical depths from CMB observations
  Ionized medium causes CMB polarization: $z_{\text{eor}} \sim 10$

• High-z galaxies
  IR drop-outs give SFR/LF to $z \sim 10$: SFR rises fast below $z \sim 10$ but there are not enough UV photons to re-ionize the Universe >>> Puzzle!

• High-z QSOs
  Gunn-Peterson troughs suggest $\sim 10\%$ neutral HI at $z \sim 7$, i.e. the end of reionization occurs close to the highest z QSO/galaxies that we observe

• High-z GRBs
  GRBs traces massive star formation. Currently rare events, but $z \sim 8.2$ GRB has been seen and could be a direct tracer of the SFR.

• Temperature of the IGM
  Extrapolation of the high-z IGM temperature suggest late reionization

• NIR/X-ray background
  Detection of NIR fluctuations made, but far above predictions.
  X-rays limit AGN contribution to reionization to $\sim 10\%$ max.

Most evidence points at substantial reionization (still) occurring at $z<10$, but its source(s) are unknown: complementary tracers are needed (i.e. HI)
What can we expect from HI brightness temperature observations?

HI emission through Cosmic Time
The quantity that is measured with radio telescopes along a given line of sight and is given by:

\[
\delta T_b = \frac{T_S - T_R}{1 + z} (1 - e^{-\tau})
\]

\[
\approx \frac{T_S - T_R}{1 + z} \tau
\]

\[
\approx 27 x_{\text{HI}} (1 + \delta_b) \left( \frac{\Omega_b h^2}{0.023} \right) \left( \frac{0.15}{\Omega_m h^2} \frac{1 + z}{10} \right)^{1/2} \times \left( \frac{T_S - T_R}{T_S} \right) \left[ \frac{\partial_r v_r}{(1 + z) H(z)} \right] \text{mK},
\]

The HI 21-cm intensity is set by a complex interplay between \textit{cosmology} and \textit{(g)astrophysics}.

See also talks by Mesinger, Semelin, Pritchard, Ahn,
Main Phases of HI

• **“Dark Ages”**
  
  $z = 30 - 200$: Most likely only accessible from space/moon and/or via total power measurements using single receivers.

• **“Cosmic Dawn”**
  
  $z \sim 30 - 15$: Formation of the first stars/galaxies that heat/couple the IGM mostly; impact on gas/spin-temp. $T_b$ fluctuations will be a mixture of density and spin-T fluctuations. Maybe there is impact by bulk-flows from recombination in this redshift range.

• **“Reionization”**
  
  $z \sim 15 - 6$: Ionizing bubbles grow around first stars/galaxies and percolate. $T_b$ is set by density fluctuations and ionized bubbles mostly.

See talks by Vedantham, Maio
Hydrogen Brightness Temperature
Global Signal

Dark Ages
Cosmic Dawn
Reionization

z= 80  30  20  14  12  10  8  6

Thermal Decoupling
First Galaxies Form
UV pumping (Wouthuysen-Field effect)
Dark Ages
(Xray) Heating
Reionization begins
Reionization ends

Pritchard & Loeb 2011

See talk Vedantham
Hydrogen Brightness Temperature
Global Signal

The history of $T_b$ can vary; hence measuring $T_b$ as function of redshift/time, provides a handle on SF, Ly-α coupling (WF), (X-ray) heating, etc.
### Summary of main effects

<table>
<thead>
<tr>
<th>Redshift range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = 1100-200$</td>
<td>Compton scattering maintains thermal coupling of gas to CMB, hence $T_{\text{spin}} = T_K = T_Y$, i.e. $T_b = 0$</td>
</tr>
<tr>
<td>$z = 200-40$</td>
<td>Adiabatic cooling of the gas [$T_K \sim (1+z)^2$] hence $T_K &lt; T_Y$. Coupling sets $T_{\text{spin}} &lt; T_Y$, leading to $T_b &lt; 0$, i.e. absorption. $T_b$ fluctuations are sources only by density fluctuation possibly bulk flows.</td>
</tr>
<tr>
<td>$z = 40-z_{\text{sf}}$</td>
<td>Gas density decreases and collisional coupling becomes ineffective and $T_{\text{spin}} = T_Y$, moving back to $T_b = 0$</td>
</tr>
<tr>
<td>$z = z_{\text{sf}}-z_\alpha$</td>
<td>First sources appear at $z_{\text{sf}}$ emitting Ly-$\alpha$ and possibly X-rays.</td>
</tr>
<tr>
<td>$z = z_\alpha-z_{\text{heat}}$</td>
<td>Ly-$\alpha$ coupling saturates and its flux does not affect $T_b$ anymore. Heating becomes significant and $T_{\text{gas}}$ fluctuations source $T_b$ fluctuations. $T_K &lt; T_Y$, hence $T_b &lt; 0$ (absorption). In some regions $T_{\text{gas}} \rightarrow T_Y$, hence $T_b &gt; 0$ (emission).</td>
</tr>
<tr>
<td>$z = z_{\text{heat}}-z_T$</td>
<td>After heating $T_K &gt; T_Y$, hence $T_b &gt; 0$ (emission). Saturation occurs at $z_T$ when $T_{\text{spin}} \sim T_K \gg T_Y$. Ionization has started.</td>
</tr>
<tr>
<td>$z = z_T-z_{\text{EoR}}$</td>
<td>Heating drives $T_K \gg T_Y$ at $z_T$ and temperature fluctuations become unimportant. $T_S \sim T_K \gg T_Y$. Dependence on $T_S$ may be neglected. Ionization fluctuations begin to dominate $T_b$ signal.</td>
</tr>
<tr>
<td>$z &lt; z_{\text{EoR}}$</td>
<td>After reionization, any remaining 21 cm signal originates primarily from collapsed islands of neutral hydrogen (damped Ly-$\alpha$ systems).</td>
</tr>
</tbody>
</table>
Hydrogen Brightness Temperature

The HI brightness temperature shows fluctuations on a range of different scales, sourced by cosmology, spin-temperature, ionization & velocities.

\[ \delta T_b = \beta_b \delta_b + \beta_x \delta_x + \beta_\alpha \delta_\alpha + \beta_T \delta_T - \delta_{\partial v} \]

- Cosmology
- Reionization
- Ly\(\alpha\) Sources
- X-ray heating
- Peculiar Velocities
- Doppler-Fluctuations

HI-density-Fluctuations
Spin-temperature-Fluctuations

Power-spectrum

\[ P_{T_b}(k, \mu) = P_{\mu^0}(k) + \mu^2 P_{\mu^2}(k) + \mu^4 P_{\mu^4}(k) + P_f(k, \mu)(k, \mu) \]

- Isotropic Term
- Terms due to peculiar velocities
- More complex Terms

Auto- and cross-terms between b, x, \(\alpha\) and T

\(\partial v\) and cross-terms between b, x, \(\alpha\) and T and \(\partial v\)
Hydrogen Brightness Temperature
Power-Spectrum

Cosmic Dawn

The first stars form in $\sim10^8 \, M_{\text{sun}}$ haloes and start coupling the spin temperature (locally) to the cold gas temperature (W-F). After some time X-ray sources(?) heat the gas and cause the spin-temperature to rise again.

At high-z HI is seen in absorption with fluctuations sourced by baryonic density fluctuations. Some time later locally the gas is heated by X-rays and locally couples to the spin-temp. causing patches in absorption and emission, sourcing $T_b$ fluctuations.

See talk Mesinger

Mesinger 2010
Reionization

After a while X-ray heating is completed and HI is only seen in emission and is still mostly neutral. Fluctuations are sourced again by density fluctuations and peculiar velocities.

Finally ionization sets in and causes bubbles to occur. The strong contrast between bubbles and neutral patches is another source of $T_b$ fluctuations.
Sensitivity limits are scale dependent but $\Delta^2_{\text{noise}} \sim \text{few mK}^2$ is where current instruments aim for in $\sim 1000$ hrs. SKA can go to $\Delta^2_{\text{noise}} \sim 0.1 \text{ mK}^2$. 
SKA precursors/pathfinders:
Current 21-cm Fluctuation Detection Experiments

- Giant Meter-wave Radio Telescope [GMRT] [India]
- Murchison Wide-field Array [MWA] [Australia]
- Precision Array for Probing the Epoch of Reionization (PAPER) [SA]
- Low Frequency Array [LOFAR] [NL/Europe]
GRMT Current Results

GMRT
Epoch of Reionization (EoR) experiment

Specs

- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- z = 8.1-9.2

Paciga et al. 2013
GMRT: Measurement of a $2\sigma$ upper limit at $(248 \text{ mK})^2$ for $k = 0.50 \text{ h Mpc}^{-1}$.

Paciga et al. 2013
MWA Current Results

Results from Proto-type:
Dillon et al. 2013

Table 1: System parameters for MWA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>150 MHz</th>
<th>200 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tiles</td>
<td>N</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Area of one tile at zenith (m²)</td>
<td>A_{eff}</td>
<td>21.5</td>
<td>19.8</td>
</tr>
<tr>
<td>Total collecting area (m²)</td>
<td></td>
<td>2752</td>
<td>2534</td>
</tr>
<tr>
<td>Receiver temperature (K)</td>
<td>T_{rcv}</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>aTypical sky temperature (K)</td>
<td>T_{sky}</td>
<td>350</td>
<td>170</td>
</tr>
<tr>
<td>bField of view (deg²)</td>
<td>Ω_p</td>
<td>610</td>
<td>375</td>
</tr>
<tr>
<td>Instantaneous bandwidth (MHz)</td>
<td>B</td>
<td>30.72</td>
<td>30.72</td>
</tr>
<tr>
<td>Spectral resolution (MHz)</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td></td>
<td>0.5 s uncalibrated</td>
<td>0.5 s uncalibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 s calibrated</td>
<td>8 s calibrated</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td>Full Stokes</td>
<td>Full Stokes</td>
</tr>
<tr>
<td>Minimum baseline (m)</td>
<td></td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Maximum baseline (m)</td>
<td></td>
<td>2864</td>
<td>2864</td>
</tr>
<tr>
<td>Angular resolution (1.5 km array)</td>
<td></td>
<td>3'</td>
<td>2'</td>
</tr>
<tr>
<td>Angular resolution (3 km array)</td>
<td></td>
<td>2'</td>
<td>1'</td>
</tr>
</tbody>
</table>

a Nijboer, Pandey-Pommier & de Bruyn (2009).
b Based on FWHM of primary beam. Imageable area is significantly larger.

Table 1
MWA-32 Instrument Parameters

<table>
<thead>
<tr>
<th>Field of View (Primary Beam Width)</th>
<th>~ 25° at 150 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Resolution</td>
<td>~ 20° at 150 MHz</td>
</tr>
<tr>
<td>Collecting Area</td>
<td>~ 690 m² towards zenith at 150 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear X-Y</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>80 MHz to 300 MHz</td>
</tr>
<tr>
<td>Instantaneous Bandwidth</td>
<td>30.72 MHz</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>40 kHz</td>
</tr>
</tbody>
</table>
MWA Current Results

MWA-32T [proto-type]:

- 22 hrs of data
- March 2010
- R.A.(J2000) = 10h 20m 0s, Decl.(J2000) = −10° 0’ 0”
- 3 x 30.72 MHz bands, centered at 123.52 MHz, 154.24 MHz and 184.96 MHz, i.e. 6.1 < z < 12.1
- 5hrs and 123.52 MHz and 154.24 MHz and 12hrs at 184.96 MHz

Upper limits on the power spectrum from z = 6.2 to z = 11.7. The lowest limit is Δ(k) < 0.3 Kelvin at 95% confidence at a comoving scale k = 0.046 Mpc$^{-1}$ at z = 9.5.

Dillon et al. 2013
PAPER Current Results

64-antenna deployment in the Square Kilometre Array South Africa (SKA-SA) reserve in the Karoo desert near Carnarvon

Current EoR results with:
32-antenna deployment at the NRAO site near Green Bank, WV
PAPER 32-antenna:

- 275 hrs of data  
  (Dec. 7, 2011 to Feb. 4, 2012)  
- 100 to 200 MHz, 2048 channels,  
- visibility integr.: 10.7 seconds

A best $2\sigma$ upper limit of $2704 \text{ mK}^2$ for $k = 0.11 \text{ h Mpc}^{-1}$ at $z = 7.7$

Heating of the neutral intergalactic medium (IGM) is necessary to remain consistent with the constraints. By $z = 7.7$ the HI has been warmed from its cold primordial state.

Parsons et al. 2013
LOFAR Current Results

LOFAR is now a European telescope with its core in the Northern Netherlands, developed by ASTRON+Dutch Universities (i.e. Netherlands, Germany, UK, France & Sweden; interests in Italy, Poland, Spain, Austria+Ukraine)

van Haarlem et al. 2013

<table>
<thead>
<tr>
<th>Area</th>
<th>Distance</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>3 km</td>
<td>(2x)24 stations</td>
</tr>
<tr>
<td>NL</td>
<td>80 km</td>
<td>14 stations</td>
</tr>
<tr>
<td>Europe</td>
<td>&gt;1000 km</td>
<td>8+ stations</td>
</tr>
</tbody>
</table>

Stations have 24 – 48 – 96 antennas/tiles

Principle of Aperture Synthesis
Array resolution: sub-arcsec to degrees

Pulsars: tied-array(s), (in)coherent sums

Sensitivity (8h, 4 MHz, Core/all NL stations)

@ 60 MHz  ~ 6.2/3.9 mJy (LBA)
@ 150 MHz ~ 310/240 μJy (HBA)
LOFAR Current Results

(split) NL HBA + LBA station

HBA (110-240 MHz)

LBA (10/30-80 MHz)
LOFAR Current Results

“Superterp” aka “Six-pack”
6 densely packed stations
LOFAR Current Results

NCP, 114 Hours

- Auto-RMS
- Cross-RMS
- Simulation

5 arcmin $\sigma$ [11.8 HWHM], 1 MHz BW

Thermal noise averages away

EoR $T_b$ simulations

114 hours, 5 arcmin $\sigma$ res., 1 MHz BW

Root the difference in quadratic between the rms and the cross-rms

Simulation: Thermal
Simulation: Residual

Zaroubi et al. 2014, in prep
Current limits, based on ~100hr (out of ~500hr) of data on the NCP reach level close to the expected based on thermal noise, but a lot of effort is currently being afforded to determine any level of additional systematics (e.g. ionosphere, side-lobes, polarization) or biases (e.g. calibration).

This is computationally expensive and complex (a lesson to be learned for SKA!)

Zaroubi et al. 2014, in prep
Why SKA(-low) is needed and why it will be transformational!

See also talks by Phil Diamond & Robert Braun, and others

Beyond Current Pathfinders: SKA-low
General Observational Objectives

Epoch of Reionization [~ 100 to ~200 MHz]
- Absorption again high-z radio source (small scale power)
- Global signal (total power) of HI (absorption/emission)
- RMS fluctuations of HI emission with redshift
- Spatial power-spectra (1,2,3D) and higher-order statistics with redshift
- HI Image data-cubes (spatial-frequency) for reionization topology

Cosmic Dawn [~50 to ~100 MHz]
- Absorption again high-z radio source (small scale power)
- Global signal (total power) of HI (absorption/emission)
- RMS fluctuations of HI emission with redshift
- Spatial power-spectra (1,2,3D) and higher-order statistics with redshift
- HI Image data-cubes (spatial-frequency) for cosmology
(1) The capability of SKA$_1$ to image $\sim$3.0 mk fluctuations of neutral hydrogen at 3-sigma level in $t_{\text{int}}$=1000 hrs at 150 MHz with BW=1 MHz, covering $z$$\sim$6-15.

(2) Capability of SKA$_1$ to cover all EoR & Dark Ages ($z$=6-30) features currently expected in the HI power-spectrum and total intensity both in emission and absorption.

(3) Allow HI absorption at sub-KHz level against high-z radio sources.

(4) The capability of SKA$_2$ to image $\sim$0.3 mk fluctuations of neutral hydrogen at 3-sigma level in $t_{\text{int}}$=1000 hrs at 150 MHz with BW=1 MHz, covering $z$$\sim$6-30. But imaging is feasible to $z$=30 after filtering (in principle).
2.4.1 Cosmic Dawn and the Epoch of Reionisation

**SKA1-SCI-1:** SKA1 shall achieve a Stokes-I brightness sensitivity of 1 mK RMS over 1 MHz on 5 arcmin angular scales at 0.1 – 0.2 GHz over a field size up to 5x5 deg$^2$ within 1000 hours of integration;

This will enable detection of individual 21cm fluctuations during the Epoch of Reionisation as well as characterising the fluctuation spectra with high precision at red-shifts of at least, $z = 6 – 13$.

**SKA1-SCI-2:** SKA1 shall achieve a Stokes-I brightness sensitivity of 1 mK RMS over 1 MHz on 1 degree angular scales at 50 - 100 MHz over a field size up to 10x10 deg$^2$ (at 50 MHz) within 1000 hours of integration;

This will enable detection of individual 21cm fluctuations during the Cosmic Dawn as well as characterising the fluctuation spectra with high precision at red-shifts below $z = 27$. 
Square Kilometre Array: SKA I - Low

Table 2 SKA1-low – Log-Periodic Dipoles

<table>
<thead>
<tr>
<th>Aperture Array</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Frequency</td>
<td>50 MHz</td>
<td>Dual polarization (2 orthogonal)</td>
</tr>
<tr>
<td>Upper Frequency</td>
<td>300 MHz</td>
<td>Single element covering full range</td>
</tr>
<tr>
<td>Number of antennas per station</td>
<td>289</td>
<td>Log-Periodic-Dipole antennas</td>
</tr>
<tr>
<td>Total physical aperture</td>
<td>8.0 x 10^7 m^2</td>
<td></td>
</tr>
<tr>
<td>Area per antenna</td>
<td>2.25 m^2</td>
<td></td>
</tr>
</tbody>
</table>

| Element filling factor in station | 0.7 | Areal filling factor |
| Dense/Sparse Transition          | 111 MHz | A_r per element is equal to packing density |

Array Configuration

| Station Diameter       | 35 m |
| Number of stations     | 911 stations |
|                      | 866 in core; 45 in spiral arms |
| Core (radius <600 m)   | ~50% (~433 st’ns) |
| Core (radius <1000 m)  | ~75% (650 st’ns) |
| Spiral Arms            | ~4% (45 stations) |
| Av‘g St’n filling factor (radius <220 m) | 0.91 | Stations must be close-packed or overlapped to radius of 650 m. |

Station Beam Forming

| Number of beams | 1 |
| Instantaneous bandwidth per beam | 250 MHz |
| Assumes full bandwidth is available (50-300 MHz) |

Digital Outputs

| Sample streams | 2 |
| bits per sample | 8 |
| Max - sub-bands | |
| Sent from Beamformers |

Signal Transport System

| Data rate per station | 10 Gb/s * |
| Radius < 3000 m      | 8.7 Tb/s  |
| 3 km < Radius < 50 km | 450 Gb/s |
| Optical fibre to signal processor |
| 866 stations |
| 45 stations |

Signal Processing System

| Fine Frequency channels** | 2.5 x 10^5 |
| Complex Correlations     | 4.1 x 10^1 |
| Complex Correlations: Spiral Arms | 0.4 x 10^1 |
| Core (radius<3 km) Dump Time | ~10.6 s |
| Minimum Dump Time        | ~0.6 s |
| Channel Bandwidth = 1 kHz |

| 911^2/2|baselines x (1) bms x 4 po'f'n prod's x 2.5 x 10^5 chans |
| (911^2-866^2) / 2 baselines |
| Station diameter = 34 m; max baseline = 6 km |
| Station diameter = 34 m; max baseline = 100 km |

Science Computing System

| Input data rate (1 kHz channels) | 842 x 10^9 |
| Input data rate (100 kHz channels) | 8.4 x 10^9 |
| Byte s^-1 av’ge from correlator (4-Byte x 2 for complex) |
| (3.8 corr’s/10.6 s + 0.3 corr’s/0.6 s) x 10^11 x 8 (8-Byte complex) |
| Assumes some preprocessing at 1 kHz, then averaging |

A=0.8 km^2; 50% in a 600m core
75% in a 1000m core
4% outer 15 stat
to 45 km radius

Station-size = 35m diameter

Freq: 50-350+MHz
Power-Spectra: Sensitivity

\[
\Delta^2_{\text{Noise}} = \left(\frac{2}{\pi}\right) k^{3/2} \left[D_c^2 \Delta D_c \times N_b \Omega_{\text{FoV}}\right]^{1/2} \left(\frac{T_{\text{sys}}}{\sqrt{B t_{\text{int}}}}\right)^2 \left(\frac{A_{\text{core}} A_{\text{eff}}}{A_{\text{coll}}^2}\right)
\]

\[
\Delta^2_{\text{Noise}} \propto \left(\frac{A_{\text{core}} \sqrt{A_{\text{eff}}}}{A_{\text{coll}}^2}\right) \propto \left(\frac{A_{\text{core}}}{N_{\text{stat}}^2 A_{\text{eff}}^{3/2}}\right) \propto \left(\frac{A_{\text{core}}}{\sqrt{N_{\text{stat}}} A_{\text{coll}}^{3/2}}\right)
\]

- **Large collecting area:** High instantaneous sensitivity (tomography!)
- **Compact configuration:** High 21-cm $T_b$ sensitivity (large filling factor)
- **Large field of view:** Lowers Cosmic/sample variance (e.g. via multi-beaming or reduced beam-forming)

- **Longer baselines** ($>>$few km) needed for calibration (gain, beam, ionosphere, polarization, etc), systematics controls/checks and FG removal, not necessarily for CD/EoR science.

SKA
SKA I - low: Power-Spectra
Power-spectrum, $z = 8.95$

Signal-to-Noise
The sweetspot for SKA will be 1 dex around $k \sim 0.1 \text{ Mpc}^{-1}$. 
SKA I-low: Power-Spectra

Integration times: $t_{\text{int}} = 1000, 2000, 5000$ hrs
SKA I-low: Power-Spectra

Multi-beaming: N=1, 4, 16
SKA2-low: Power-Spectra

Collecting area x 4, Baselines x 2, multi-beaming: N=1, 4, 16
SKA can probe physics of the EoR and CD with high S/N

S/N of peak of power spectrum

See talk Mesinger

Min. halo mass

X-ray heating

Mesinger et al. 2013
Why SKA?

Current pathfinders can only do statistical detection and probe limited part of model space.

SKA can probe all reasonable parameter space with high (~100) S/N.

Mesinger et al. 2013
Why SKA?

Current pathfinders can only do statistical detection and probe limited part of model space. SKA can probe all reasonable parameter space with high (~100) S/N.
HI 21-cm $T_b$ fluctuations occur on $\sim$1mK scales and larger; ionized bubbles have $\sim$30mK contrast. This can be reached on scales of several tens of arcminutes over most of the CD/EoR z-range.

\[
\Delta T = \left( \frac{k_\perp}{2\pi} \right) \left[ D_c^2 \times \Omega_{\text{FoV}} \right]^{1/2} \left( \frac{T_{\text{sys}}}{\sqrt{B t_{\text{int}}}} \right) \sqrt{\left( \frac{A_{\text{core}} A_{\text{eff}}}{A_{\text{coll}}^2} \right)}
\]

\[
= \left( \frac{k_\perp}{2\pi} \right) \left[ D_c^2 \times \Omega_{\text{core}} \right]^{1/2} \left( \frac{T_{\text{sys}}}{\sqrt{B t_{\text{int}}}} \right) f_{\text{fill}}^{-1}
\]

\[
= \left( \frac{T_{\text{sys}}}{\sqrt{B t_{\text{int}}}} \right) f_{\text{fill}}^{-1}
\]

<table>
<thead>
<tr>
<th>Scale</th>
<th>150MHz</th>
<th>70MHz</th>
<th>$f_{\text{fill}}$ (150/70)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5'</td>
<td>7</td>
<td>11mK</td>
<td>0.03/0.1</td>
</tr>
<tr>
<td>20'</td>
<td>0.7mK</td>
<td>1.1mK</td>
<td>0.3/1.0</td>
</tr>
<tr>
<td>60'</td>
<td>0.7mK</td>
<td>1.1mK</td>
<td>0.3/1.0</td>
</tr>
</tbody>
</table>

1000hrs, 1MHz, $T_{\text{sys}}$=400/2000K, $\nu_{\text{opt}}$=100MHz

see also talks Mellema, Wyithe
Tomography is feasible on 10' scales over the redshift z<15 range.

Tomography is feasible on 5' scales over the redshift z<8 range.

Tomography is feasible on 1° scales over the redshift z=6-25 range.

EoR: z<15
In 1000hr with a BW=1MHz or matched to angular scales, one can do tomography to the required level of ~1mK on scale >~10'.

Cosmic Dawn: 15<z<25
Idem, on scales >~1°.
Summary & Conclusions

• Observations of Ly-α emitters, dropouts, QSOs, GRBs, NIR/Xray BGs are starting to probe the first stars/galaxies to z~10, during the EoR.

• HI is the only tracer that allows us to study many processes during the Dark Ages, Cosmic Dawn & EoR over wide range of angular scales.

• Currently four HI/EoR detection experiments are ongoing: GMRT, MWA, PAPER and LOFAR. No detection yet, but increasingly stronger upper limits. All experiments are statistical in nature [e.g. power-spectra/excess variance]

• Near Future: New or extensions of current arrays to probe Cosmic Dawn: AARTFAAC/NenuFAR/LWA-LDA/HERA

• SKA will allow tomography (imaging!) to z=25 [Cosmic Dawn]

• To detect the Dark Ages we need to go in to space or to the moon.

9 June 2014, Advancing Astrophysics with the Square Kilometre Array, Giardini Naxos, Italy