Cosmic Dawn & Epoch of Reionization with SKA1-low: SWG & Science Team

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Science Goals
SKA EoR/CD SWG/ST
Why and How Study the Universe’s First Gyr?

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

Cosmic Dawn
- Appearance of first stars/BHs (PopIII?)
- Ly-α 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

Post-Reionization
- BAO - DE EoS/Gravity
- Intensity Mapping - DE EoS/Gravity
- Galaxy Counts - Mass function ++
Studying HI Through Cosmic Time

The tomography of HI emission is a treasure trove of information for (astro)physics, cosmology & fundamental physics.

Post-Reionization
HI is found largely in galaxies

Dark Ages/Cosmic Dawn/Reionization
HI has a filling factor of order unity

Credit: Dixon, Illiev et al.
CD/EoR Survey Designs

Wider versus Deeper

A three tiered-survey (3x5,000hrs):
- DEEP: 100sqd with 1000hr/pointing
- MEDIUM: 1000sqd with 100hr/pointing
- SHALLOW: 10000sqd with 10hr/pointing

Deeper is better on small scales (less thermal noise; bubbles)
Wider is better on large scales (less sample variance)
Both are needed (PS+Tomography)

Greig, Mesinger & Koopmans (in prep)
EoR/CD: 21-cm Power-Spectrum

Free parameters:

- Escape fraction ($f_{\text{esc}}$)
- Minimum $T_{\text{vir}}$ for SF
- Mean Free Path photons

Uses 21CMMC (Greig & Mesinger 2015)

For model details see Greig, Mesinger & Koopmans (in prep)
Direct EoR Imaging: 21-cm Tomography

Topology of EoR provides much more information on the sources than a power-spectrum, but requires a lot more sensitivity.
Current Status
21-cm Cosmology
Global 21-cm Signal Detection?

Correct redshift but 2.5x deeper than possible in standard model.

Spectacular but needs confirmation (e.g. by SARAS2).

Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case. Each profile for the brightness temperature $T_{21}$ is added to its residuals and plotted against the redshift $z$ and the corresponding age of the Universe. The thick black line is the model fit for the hardware and analysis configuration with the highest signal-to-noise ratio (equal to 52, H2; see Methods), processed using 50–99 MHz and a four-term polynomial (see equation (2) in Methods) for the foreground model. The thin solid lines are the best fits from each of the other hardware configurations (H1, H3–H6). The dash-dotted line (P8), which extends to $z > 26$, is reproduced from Fig. 1c and uses the same data as for the thick black line (H2), but a different foreground model and the full frequency band.

Bowman et al. 2018
Current 21-cm Power-Spectrum Detection Experiments

**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

**MWA**

Murchison Widefield Array

Specs:
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = −30° 0′ 0′′
- high-band of 30.72 MHz, centered at 182 MHz i.e. 6.2 < z < 7.5

Dillon et al. 2015

**LOFAR**

International LOFAR Telescope (ILT)

Specs:
- 13 hrs of data; - Feb 11/12 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = 90° 0′ 0′′
- high-band of 115-189 MHz

Ali et al. 2015
GMRT: Measurement of a $2\sigma$ upper limit of $\Delta(k) < 248$ mK for $k = 0.50$ h Mpc$^{-1}$ at $z = 8.6$.

Paciga et al. 2013

MWA-128T: Upper limits on the power spectrum from $z = 6.2$ to $z = 7.5$. The lowest limit is $\Delta(k) < 192$ mK at 95% confidence at a co-moving scale $k = 0.18$ Mpc$^{-1}$ at $z = 6.8$.

Dillon et al. 2015

PAPER 64-antenna: A best $2\sigma$ upper limit of $\Delta(k) < 22$ mK for $k = 0.15$-0.5 h Mpc$^{-1}$ at $z = 8.4$.

Ali et al. 2015

LOFAR: Measurement of a $2\sigma$ upper limit of $\Delta(k) < 80$ mK for $k = 0.05$ h Mpc$^{-1}$ at $z = 10.1$.

Patil et al. 2017
Current 21-cm Power-Spectrum Detection Experiments

By far the deepest 21-cm power spectrum results to date
Our SWG (advices SKAO) mirrors a single Science Team (prepares for KSP) that aims to transition to a single Key Science Project Team with internally various science goals/groups. No split!
Welcome to the Google Site for the SKA CD/EoR Science team. This site will be used as a central information hub where we will place any information, documents, etc. relevant for the SKA CD/EoR Science Team.

Our Google Group can be found by clicking here.
Focus Groups

This page lists the focus groups and a short description of their focus. The full list can be found in the [List of Focus Groups](#) document.

A) Theory/numerical simulations
   A1: Theory/physics for understanding model space/subgrid physics
   A2: Full numerical simulations for calibration
   A3: Fast simulations for analysis
   A4: Foreground studies and simulations

B) Observational strategies
   B1: Interferometric
   B2: Global signal
   B3: 21cm forest

C) Data processing
   C1: RFI excision
   C2: Calibration/ionosphere
   C3: Imaging/sky-model building
   C4: Foreground fitting/removal
   C5: New algorithmic development
   C6: Computational and other resources

D) Signal extraction and error analysis

E) Signal analysis and interpretation

F) Synergy (SKA + Other instruments)

G) End-to-end (data) simulations
Membership/Dutch Involvement and leadership

- Membership SWG in principle open to all CD/EoR researchers (email Chairs: Mellema/Bernardi)

- Membership Science Team open to all CD/EoR researchers (email Chair Koopmans) that want to actively participate in one or more Focus Group(s).

- First Associate Member and if genuinely active they become Core Member after ~1 year.

- Some guidelines by SKA board are that SKA member states are reasonably represented (~10% from non-member states). Current ST board has member from each member state.
Regular SWG/Science Team Meetings

Current Focus: Data Challenges from raw data to 21-cm signal

First challenge will be announced in Sept. 2018

SKA CD/EoR Science Team
Contributions SWG/ST to SKA1-low

• Propose (adopted) SKA1-low baselines design (Mellema, LVEK et al. 2013)
• Play central role in define HPSCs (High Priority Science Cases)
• Play central role in the (first) re-baselining effort, ensuring SKA1-low remains able to do transformational science (21-cm tomography, Cosmic Dawn)
• Help define many aspects (bandpass smoothness, layout, station size, etc)
• Help develop some of the data processing/analysis tools (NL Roadmap contribution by e.g. Koopmans++, DIRAC project by Yatawatta++, etc.)
• Help define transition point in SDP from SKAO -> Community
• Develop distributed processing/calibration/imaging (e.g. SageCal-CO can now run globally distributed, with successful test between NL-AU) and other processing tools/algorithms. Use lessons from LOFAR & MWA.
Challenges

- A 3 tiered survey will take ~5 years and collect ~1 exabyte of data !!
- Processing requires 10s-100s Pflops for many years with current algorithms.
- Where to place the data, centrally/distributed? Distribute per over time of over frequency? Task for SKA Regional Centres ?
- What algorithms/tools are needed to get the data to the ~thermal noise level on the shortest baselines (are current algorithms good enough)
- Incorporate lessons learned from all precursors/pathfinders in to a design/processing chain. SKA1-low is LOFAR on steroids! Perfect pathfinder!
- We are involved in SKAO “Data Challenge” discussion (reality check!)
- SWG/ST plans its own end-to-end “Data Challenges” in the next years that increase in complexity. Challenges on simulated data, real (LOFAR/MWA) data and also on early-science/release data from SKA1-low.
- Lack of people-power as always!
Issues

• A 3 tiered EoR/CD Survey program would be ~1 exabyte of data. SKA project will not be able to process this to mK depths w/o help from experts in the EoR community. SKAO does not have this expertise.

• Data processing needs handover point to community (either on SKA HPC or externally). What point? Discussion with SDP ongoing.

• Difficult sometimes to transfer knowledge from precursors/pathfinders to the SKAO (e.g. Roadmap/DIRAC/LOFAR-EoR, etc). Lack of people to handle all of this at SKAO and in external teams.

• We need clarity on KSPs sooner rather than later to start requesting resources (e.g. ERC, etc). Pre-allocation (w/clear requirements) would be extremely helpful to obtain these resources. Data in role-out phase is already useful to obtain power-spectra on large scales, but not for tomography.