Constraining Cosmic Dawn and Reionization
Astrophysics with the SKA

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Cosmic history

Reionization

$z = 0$
$t_{age} \sim 14 \text{ Gyr}$

$z \sim 6$
$t_{age} \sim 1 \text{ Gyr}$

$z \sim 20$
$t_{age} \sim 150 \text{ Myr}$

$z \sim 1100$
$t_{age} \sim 0.4 \text{ Myr}$

Lots of neutral hydrogen!
Cosmic history in 21cm

Reionization

Cosmic Dawn

Dark Ages

\( z \approx 0 \)

\( z \approx 6 \)

\( \text{age} \approx 14 \text{ Gyr} \)

\( \text{age} \approx 1 \text{ Gyr} \)

\( z \approx 20 \)

\( \text{age} \approx 150 \text{ Myr} \)

\( z \approx 1100 \)

\( \text{age} \approx 0.4 \text{ Myr} \)

First Black Holes

Infancy of Cosmic Web

First Stars
\[ \delta T_b(\nu) \approx 27 \chi_{\text{H}_2} (1 + \delta_{\text{HI}}) \left( \frac{H}{(dv_r/dr + H)} \right) \left( 1 - \frac{T_{\gamma}}{T_s} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_M h^2} \right)^{1/2} \left( \frac{\Omega_B h^2}{0.023} \right) \text{mK} \]
Cosmological 21cm Signal

\[
\delta T_b(\nu) \approx 27\chi_{HI}(1 + \delta_m) \left( \frac{H}{dv_r/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_M h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \text{mK}
\]

Powerful probe:

Cosmology & Astrophysics

Has something everyone can enjoy!
The trick is to disentangle the components:

• separation of epochs and/or
• efficient modeling and robust predictions
Global evolution: $dT_b$

\[
\delta T_b(\nu) \approx 27 x_{\text{HI}}(1 + \delta_{\text{nl}}) \left( \frac{H}{\frac{\text{d}v}{\text{d}r} + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( 1 + 0.15 \frac{z}{10} \frac{\Omega_M h^2}{0.023} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \text{mK}
\]

Main stages:
- Collisional coupling ($z \sim 100$)
Global evolution: $dT_b$

$$\delta T_b(\nu) \approx 27x_{HI}(1 + \delta_{nl}) \left( \frac{H}{dv/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_M h^2} \right)^{1/2} \frac{\Omega_b h^2}{0.023} \text{ mK}$$

Main stages:
- Collisional coupling ($z \gg 100$)
- Collisional decoupling ($25 < z < 100$)
Global evolution: $dT_b$

$\delta T_b(\nu) \approx 27x_{HI}(1 + \delta_{HI}) \left( \frac{H}{dv/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( 1 + z \right) \left( \frac{0.15}{10} \right) \left( \frac{\Omega_M h^2}{0.023} \right) \text{ mK}$

Main stages:
- Collisional coupling ($z > \sim 100$)
- Collisional decoupling ($25 < z < 100$)
- WF coupling ($\text{Ly}\alpha$ pumping)
Global evolution: \( dT_b \)

\[
\delta T_b(\nu) \approx 27x_{\text{HI}}(1 + \delta_{\text{HI}}) \left( \frac{H}{dv/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \right) \left( \frac{0.15}{\Omega M h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \text{mK}
\]

Main stages:

- Collisional coupling \((z > \sim 100)\)
- Collisional decoupling \((25 < z < 100)\)
- WF coupling (\(\text{Ly}_\alpha\) pumping)
- IGM heating (X-rays)
Global evolution: $dT_b$

Main stages:
- Collisional coupling ($z > \sim 100$)
- Collisional decoupling ($25 < z < 100$)
- WF coupling ($\text{Ly}\alpha$ pumping)
- IGM heating (X-rays)
- Reionization

\[
\delta T_b(\nu) \approx 27x_{\text{HI}}(1 + \delta_{\text{HI}}) \left( \frac{H}{dv/dr + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( 1 + \frac{z}{10} \frac{0.15}{\Omega_M h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \, \text{mK}
\]
Global evolution: \( dT_b \)

\[
\delta T_b(\nu) \approx 27 x_{\text{HI}}(1 + \delta_{\text{HI}}) \left( \frac{H}{dv/\text{d}r + H} \right) \left( 1 - \frac{T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \frac{0.15}{\Omega_M h^2} \right)^{1/2} \left( \frac{\Omega_b h^2}{0.023} \right) \text{ mK}
\]

Order robust but likely overlap!

**Main stages:**
- Collisional coupling \((z > \sim 100)\)
- Collisional decoupling \((25 < z < 100)\)
- WF coupling (Ly\(\alpha\) pumping)
- IGM heating (X-rays)
- Reionization

**DARK AGES**

**COSMIC DAWN**
Fiducial evolution of large-scale power

- SKA-1 allows us to peer into the infancy of galaxy formation. Characteristic 3-peaked evolution (e.g. Pritchard & Furlanetto 2007; Baek+2010):

$WF$ coupling

$H$ cooling galaxies
Fiducial evolution of large-scale power

- SKA-1 allows us to peer into the infancy of galaxy formation. Characteristic 3-peaked evolution (e.g. Pritchard & Furlanetto 2007; Baek+2010):

WF coupling
X-ray heating

H cooling galaxies
Fiducial evolution of large-scale power

- SKA-1 allows us to peer into the infancy of galaxy formation. Characteristic 3-peaked evolution (e.g. Pritchard & Furlanetto 2007; Baek+2010):

**Diagram:**

- WF coupling
- X-ray heating
- Reionization

H cooling galaxies
First galaxies drive WF coupling

- SKA-1 allows us to peer into the infancy of galaxy formation. Characteristic 3-peak evolution (e.g. Pritchard & Furlanetto 2007; Baek+2010):

If we do not detect the 3rd peak, minihalos play a major role.
Arguably the most exciting prospect is detecting the heating of the IGM peak signal!

1\textsuperscript{st} gen.

LOFAR, MWA, PAPER, 21CMA

2\textsuperscript{nd} gen.

SKA, HERA
Redshift of X-ray peak

simple observable $\rightarrow$ which halos hosted early galaxies and what were their X-ray luminosities

X-ray luminosity/SFR

AM+2014
Redshift of X-ray peak

simple observable → which halos hosted early galaxies and what were their X-ray luminosities

SKA1 is cosmic variance limited in this regime

$X$-ray luminosity/SFR

AM+2014
But we can learn more!

X-ray mfp is an extremely strong function of energy $\rightarrow$ the patchiness of the heating tells us about the SED and high-energy processes of early galaxies.
What are the dominant high-energy processes?

Composite SEDs of local, star-forming galaxies

Luminosities of both hot ISM (soft) and HMXB (hard) scale with SFR

Based on observations in Mineo+2012a,b
X-ray SED from 21cm fluctuations

X-ray luminosity/SFR

Pacucci, AM+ (2014)
Robustly extracting SED from 21cm fluctuations

Pacucci, AM+ (2014)

'Soft' SED, dominated by hot ISM

'Shard' SED, dominated by HMXBs

X-ray luminosity/SFR

factor of 3 in power amplitude, not degenerate with $M_{\text{min}}$ & $f_x$
Added sensitivity and resolution of SKA gives us leverage on EoR physics
Generic features of EoR

\[
\Delta_{21}^2 = \bar{T}_b^2 \left[ \Delta_{xx}^2 - 2\bar{x}_{\text{HI}} \Delta_{xd}^2 + \bar{x}_{\text{HI}} \Delta_{dd}^2 \right]
\]

1\textsuperscript{st} gen. aiming at the peak

AM+2013
EoR sources

but SKA lets us dig into the physics...

If the EoR is driven by small, faint galaxies (less biased halos), the power spectrum is steeper

Iliev+(2012)
EoR feedback on Sinks and Sources

- Photons are lost to balance recombinations primarily in large HII regions
- This has an additive impact with UVB feedback on sources

Sobacchi & AM (2014)

suppression of large-scale 21cm power by factors of >3-5 throughout reionization, and a steeper spectrum (mostly due to inhomogeneous recombinations).
suppression of large-scale 21cm power by factors of >3-5 throughout reionization, and a steeper spectrum (mostly due to inhomogeneous recombinations).
Conclusions

- The timing and duration of the initial rise and fall of the 21cm power tell us about star-formation inside the very first, molecularly-cooled galaxies. Efficient star-formation inside these minihalos could source WF coupling fluctuations at $z > 30$.

- The peak amplitude of the large-scale 21cm power during X-ray heating is sensitive to the SEDs of the first galaxies (at the factor of few level), while the redshift of the peak tells us about their X-ray luminosity and host DM halos.

- The early stages of the EoR, $x_i \sim 0.1-0.2$, are characterized by a drop in large-scale 21cm power amplitude, and a steepening of the power spectrum. The timing and duration of this feature tells us about the contribution of X-rays to the EoR.

- The midpoint of the EoR is characterized by a local maximum in large-scale 21cm fluctuations (driven by the ionization field), except if hard X-rays dominate reionization.

- The morphology of the EoR encodes information about the efficiency of star-formation inside galaxies, feedback processes and absorption systems.

- Absorption systems inhibit growth of large HII regions, dramatically reducing large-scale 21cm power (by factors of 2–5).

- The 21cm forest, if detected either through individual sightlines or statistically through the rise in small-scale ($k > 0.5$/Mpc) 21cm power, will constrain the population of radio-loud AGN.
X-ray heating from early galaxies

- New window (1st gen will likely not detect thermal evolution)

$SKA-1$ is cosmic variance limited

$EoR$ $Heating$

Mesinger+2014