From the Dark Ages to Reionization with CMB-S4

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CMB-S4 Summer Collaboration Meeting
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what we know

Universe significantly ionized at z < 6 (quasar spectra)

Universe significantly neutral at z > 10 (large-scale CMB polarization)

Driven by ionizing radiation from stars (high-z galaxy and AGN luminosity functions)

Characterized by ionized bubbles a few to hundreds of comoving Mpc across (extrapolation)

what we don’t know

What was the mean ionized fraction vs redshift, i.e. the reionization history?

How did the sizes and morphologies of the ionized bubbles change with time?

What were the sources of reionization, and how do they differ from galaxies observed later?

How did the first supermassive black holes, with masses as large as $10^9 \, M_{\odot}$, form?
Reionization involves a broad range of astrophysical processes

**astrophysical processes**

- first star & black hole formation
- evolution of multiphase ISM
- early galaxy formation

**model parameters**

- spectral energy distribution
- ionizing photon escape fraction
- luminosity and abundance
- cloud size & abundance
- clumping factor

**energetics of multiphase ISM**

**radiative feedback on the IGM**

**photon sources**

**photon sinks**
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- Evolution of multiphase ISM
- Early galaxy formation
- Energetics of multiphase ISM
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Ionization history & morphology

Photon sources

Photon sinks
A Diverse Landscape of Observational Probes

**electrons**
ionization and thermal history, morphology
CMB (SO, CMB-S4, LiteBIRD)

**intergalactic hydrogen**
ionization and thermal history, morphology
Ly-alpha forest, 21cm (HERA, SKA)

**galaxy emission**
Line intensity mapping (COMAP, TIME, CONCERTO, FYST, SPHEREx)
Lyman-break galaxies (JWST)
Galaxies from the epoch of reionization are distant and faint

Oesch et al. (2018)
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Large scale CMB polarization constrains optical depth
Large scale CMB polarization constrains optical depth and possibly more...

see talk by Xiaohan Wu
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CMB probes patchiness of reionization through electron scattering

**SOURCE**
- CMB monopole
  - patchy electrons + peculiar velocity
- CMB temperature quadrupole
  - patchy electrons
- CMB primary anisotropies
  - patchy tau

**OBSERVABLE**
- CMB probes patchiness of reionization through electron scattering
  - **temperature**
    - \( \ell \gtrsim 500 \)
  - **polarization**
    - \( \ell \gtrsim 50 \)
  - **temperature + polarization**
    - \( \ell \gtrsim 50 \)
CMB probes patchiness of reionization through electron scattering

CMB-S4 has the statistical power to constrain the optical depth to ~5% accuracy assuming we can model patchiness well enough and that non-patchy contribution is negligible.
CMB probes patchiness of reionization through electron scattering

**SOURCE**
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  - patchy electrons + peculiar velocity
- CMB temperature quadrupole
  - patchy electrons
- CMB primary anisotropies
  - patchy tau

**OBSERVABLE**
- kinetic SZ
  - temperature $\ell \gtrsim 500$
- “scattering”
  - polarization $\ell \gtrsim 50$
- “screening”
  - temperature + polarization $\ell \gtrsim 50$

see talks by
- Suvodip Mukherjee
- Paul La Plante
- Toshiya Namikawa
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The 21cm transition probes neutral hydrogen during reionization

Radio interferometers such as HERA and SKA search for the 21cm signal from reionization at ~100 - 200 MHz

These observations promise to measure the power spectrum and map out the ionized bubbles in 3D, but are extremely challenging, with only upper limits so far
The 21cm transition probes neutral hydrogen during reionization

Kolopanis et al. (2019)

Most recent
LOFAR Upper Limits

Mertens et al. (2020)

See talk by Josh Dillon
The CMB-S4 large area survey overlaps with 21cm surveys: is there a detectable cross-correlation?

See talk by Paul La Plante
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see talk by
Patrick Breysse
Talks in Dark Ages to Reionization Parallel Session

11:20–11:40   Jordan Mirocha: *Overview of high-z sources*

11:40–11:55   Suvodip Mukherjee: *Physical modeling of patchy reionization*

11:55–12:10   Xiaohan Wu: *The high-redshift tail of reionization & low-ell CMB*

12:10–12:25   Patrick Breysse: *Status of reionization-era line intensity mapping*

~20 minute break

13:45–13:00   Paul La Plante: *Cross-correlating patchy kSZ with other probes*

13:00–13:15   Toshiya Namikawa: *Optical depth - Compton-y cross-correlation*

13:15–13:30   Josh Dillon: *First upper limits from HERA on 21cm power spectrum*

13:30–14:00   Discussion
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summary talk by **Zhilei Xu**