The 21 cm Frontier

Steve Furlanetto
Yale University
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What do bigger 21 cm instruments buy us?
- Imaging
- Statistical studies
- Higher redshifts
- Angular coverage
- The 21 cm forest

What other probes will we have?
- Competition
- Synergy
The 21 cm Signal

For movie, see
http://pantheon.yale.edu/~am834/

Mesinger & Furlanetto (2007)
First generation can (barely) detect structures with modest resolution

SKA or SKA pathfinder can securely detect quickly

Wyithe et al. (2005)
Future Directions

- Better imaging
  - Quasars should become easy
  - Some imaging of “normal” reionization
  - More collecting area!
  - Longer baselines for higher angular resolution
    (1 arcmin = 2 Mpc)
Reionization from 21 cm Surveys

For movie, see
http://pantheon.yale.edu/~am834/

Mesinger & Furlanetto (2007)
Error Estimates: $z=8$

- **Survey parameters**
  - $z=8$
  - $T_{\text{sys}}=440$ K
  - $t_{\text{int}}=1000$ hr
  - $B=6$ MHz
  - No systematics!

- **MWA (solid black)**
  - $A_{\text{eff}}=7000$ m$^2$
  - 1.5 km core

- **SKA (dotted blue)**
  - $A_{\text{eff}}=1$ km$^2$
  - 5 km core

- **LOFAR very close to MWA**
Pushing to Smaller Scales

MWA

SKA

For movie, see
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Mesinger & Furlanetto (2007)
Future Directions II

- Better imaging
- **Smaller scales**
  - More detailed statistics
  - Dynamic range could be key for interpreting observations
  - More collecting area!
  - Longer baselines help (few km)
Error Estimates: $z=12$

- Survey parameters
  - $z=12$
  - $T_{\text{sys}}=1000$ K
  - $t_{\text{int}}=1000$ hr
  - $B=6$ MHz
  - No systematics!
- MWA (solid black)
  - $A_{\text{eff}}=9000$ m$^2$
  - 1.5 km core
- SKA (dotted blue)
  - $A_{\text{eff}}=1$ km$^2$
  - 5 km core
The First X-rays

- X-ray photons heat gas near sources
- Hot IGM near dense gas, cool IGM near voids
- High contrast fluctuations!
- Map era of first quasars, stellar remnants, Pop III stars (?)
Future Directions III

- Better imaging
- Smaller scales
- **Higher redshifts**
  - Farther back in reionization, and first sources
  - More collecting area in compact core
  - Optimize design for lower frequencies
Redshift Space Distortions

Overdensities and underdensities are AMPLIFIED along line of sight.

Amplification depends on velocity (dark matter) and measures cosmology.
Anisotropies in the Signal

- Survey parameters
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- LOFAR very close to MWA
Future Directions IV

- Better imaging
- Smaller scales
- Higher redshifts
- Redshift space distortions
  - More information, especially on “fundamental” cosmology
  - Requires long baselines
The 21 cm Forest

Advantages
- Probes individual features and objects
- Can see the smallest-scale structure allowed to exist
- No foregrounds

Disadvantages
- Requires high-z quasars!
- Isolated lines of sight
- Large collecting area

Carilli et al. (2002)
Future Directions V

- Better imaging
- Smaller scales
- Higher redshifts
- Redshift space distortions
- **The 21 cm Forest**
  - Unique small-scale information
  - Requires sources!
  - More collecting area
The Competition

- **CMB**: integrated measurements of reionization (ACT, SPT, Planck)
  - Will help pin down reionization redshift
- **Quasar and GRB spectra**
  - Best method so far, but potential may be limited
- **Galaxy surveys**: study sources, not IGM
  - Near-term: LAEs from ground-based cameras
  - Longer term: JWST, JDEM, TMT
The 21 cm-Galaxy Cross-Correlation

- Can be done with LAEs or LBGs
- Significant advantages in 21 cm data analysis (SF & AL 2007)
- Challenge: wide-field near-IR surveys
  - JWST?
  - JDEM?
  - Ground-based cameras?

Lidz, Zahn, & Furlanetto (in prep)
Conclusions

- MWA, LOFAR, PAPER are only the first steps. Improvements help with...
  - True imaging
  - Better statistics and dynamic range
  - Higher redshifts
  - Redshift space distortions
  - 21 cm forest?
- Most robust information may come from cross-correlation with other data sets (galaxies)
- Key questions:
  - Frequency coverage
  - Weighting small vs. large scales
  - Candidates for cross-correlation/21 cm forest
  - ...and can we even do it?!?