

The 21 cm Frontier

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Outline

- 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

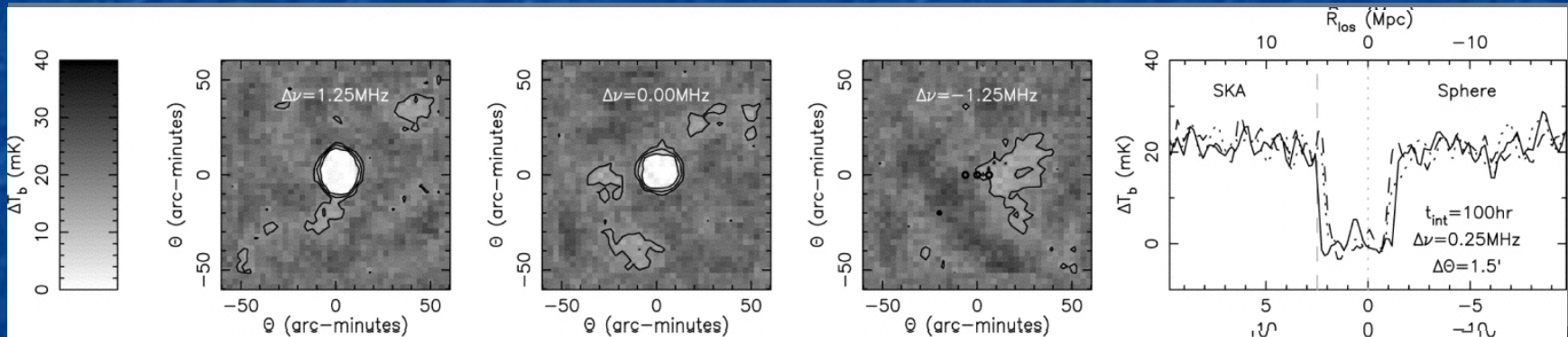
For movie, see

<http://pantheon.yale.edu/~am834/>

QuickTime™ and a
mpeg4 decompressor
are needed to see this picture.

Mesinger & Furlanetto (2007)

21 cm Imaging: Quasar HII Regions



Wyithe et al. (2005)

- First generation can (barely) detect structures with modest resolution
- SKA or SKA pathfinder can securely detect quickly

Future Directions I

- 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

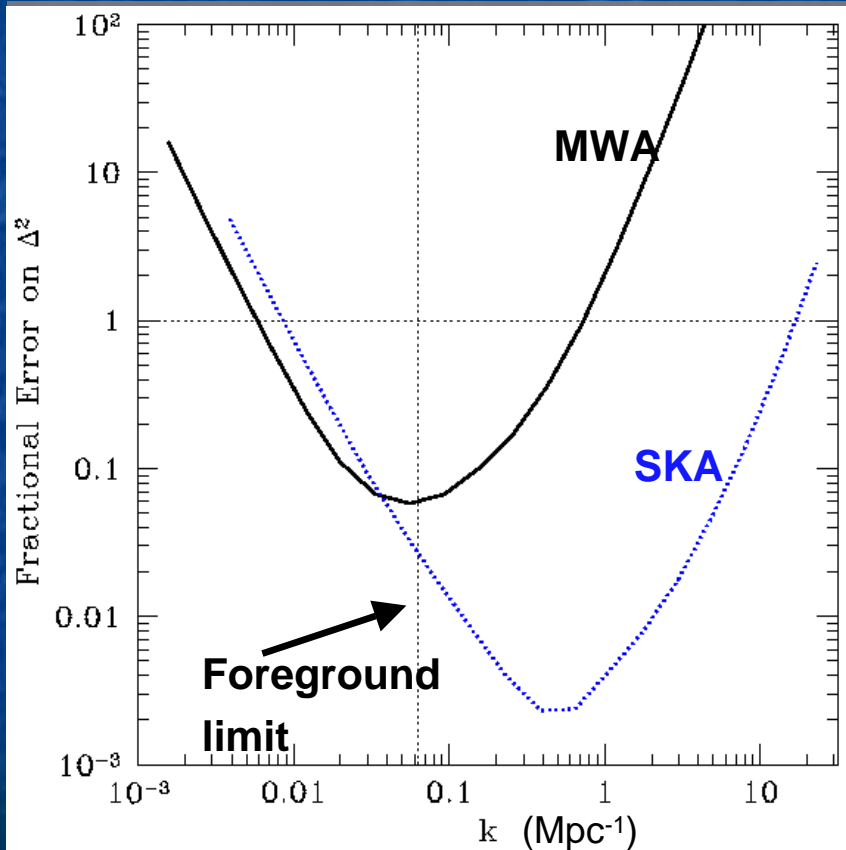
For movie, see

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mpeg4 decompressor
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Mesinger & Furlanetto (2007)

Error Estimates: $z=8$



- Survey parameters
 - $z=8$
 - $T_{\text{sys}}=440 \text{ K}$
 - $t_{\text{int}}=1000 \text{ hr}$
 - $B=6 \text{ MHz}$
 - No systematics!
- MWA (solid black)
 - $A_{\text{eff}}=7000 \text{ m}^2$
 - 1.5 km core
- SKA (dotted blue)
 - $A_{\text{eff}}=1 \text{ km}^2$
 - 5 km core
- LOFAR very close to MWA

Pushing to Smaller Scales

MWA



SKA



MWA

For movie, see

<http://pantheon.yale.edu/~am834/>

QuickTime™ and a
mpeg4 decompressor
are needed to see this picture.

SKA

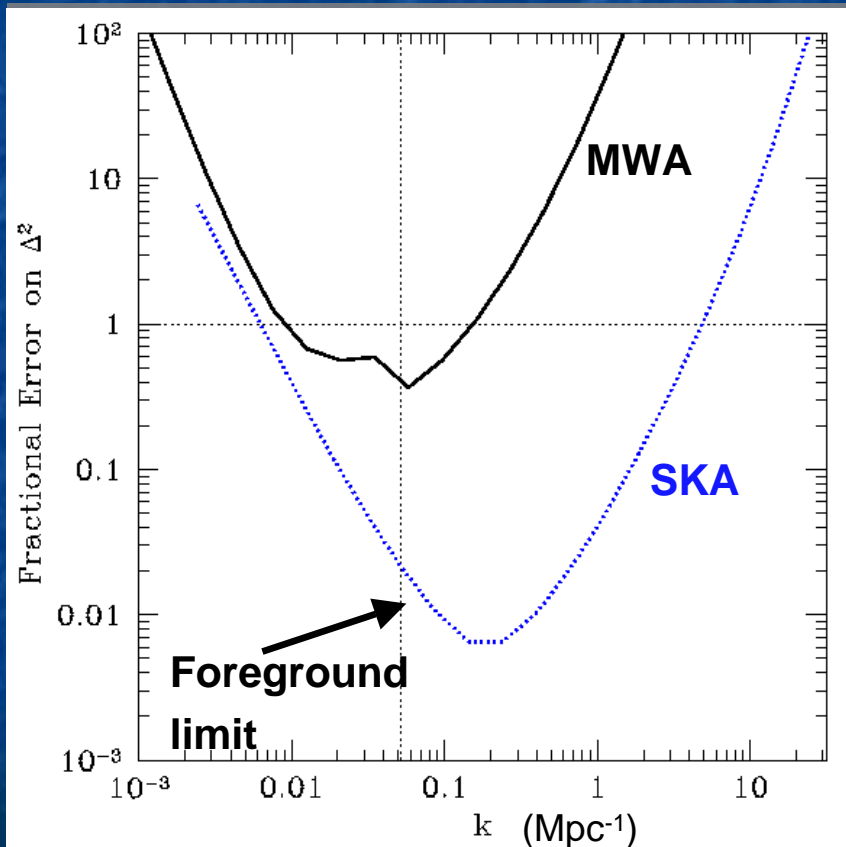
(Mpc⁻¹)

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)

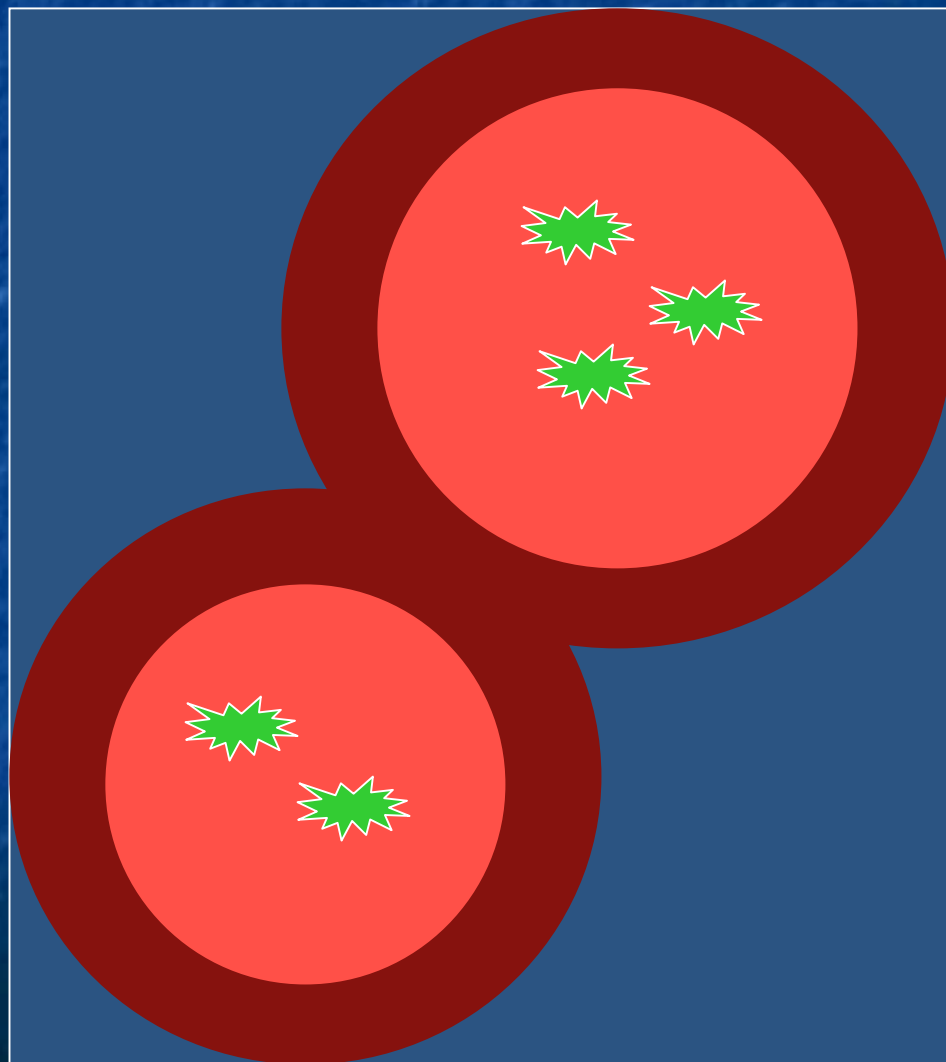
Error Estimates: $z=12$



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

The First X-rays

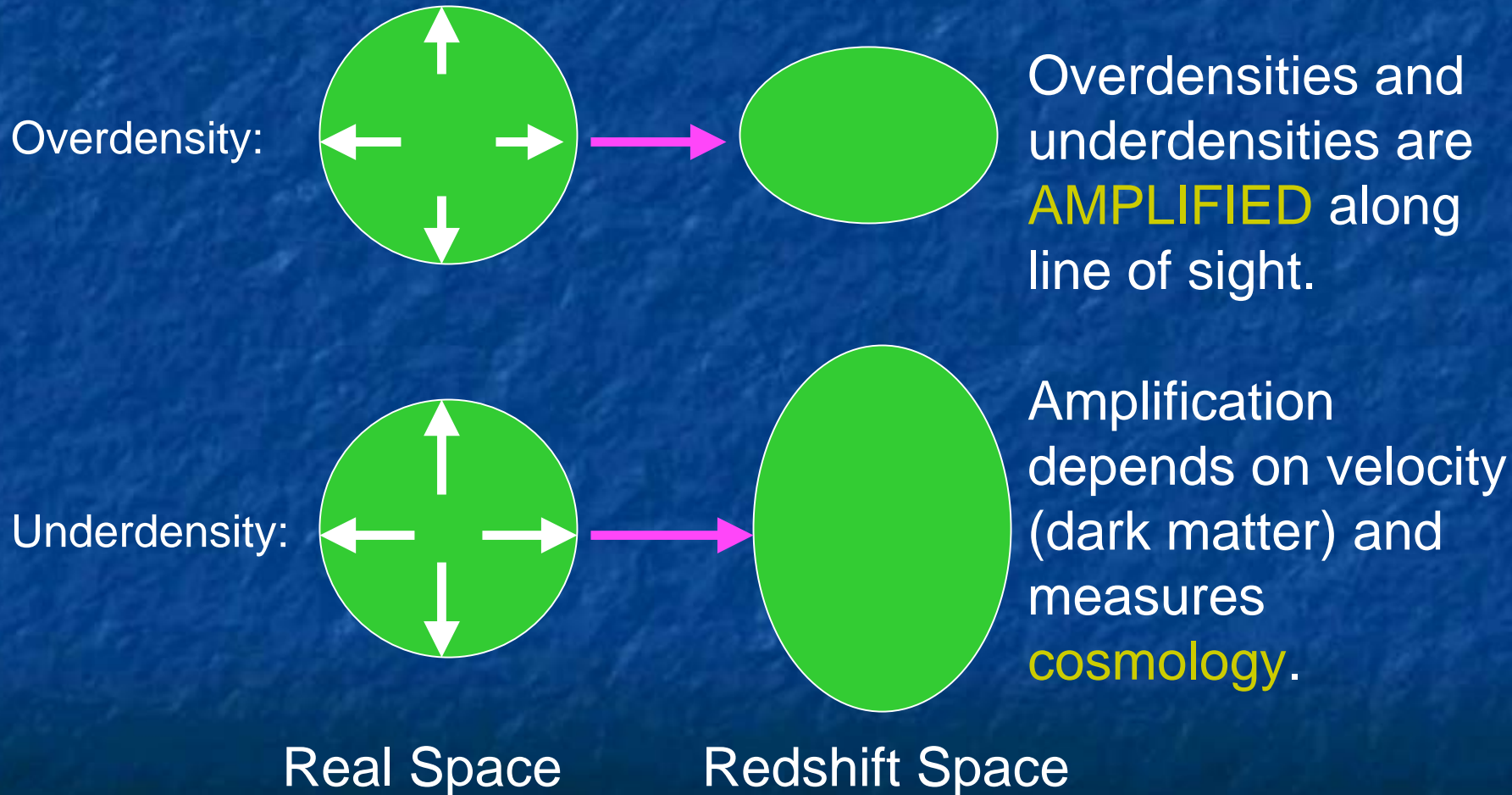
- X-ray photons heat gas near sources
- Hot IGM near dense gas, cool IGM near voids
- High contrast fluctuations!
- Map era of first quasars, stellar remnants, Pop III stars (?)



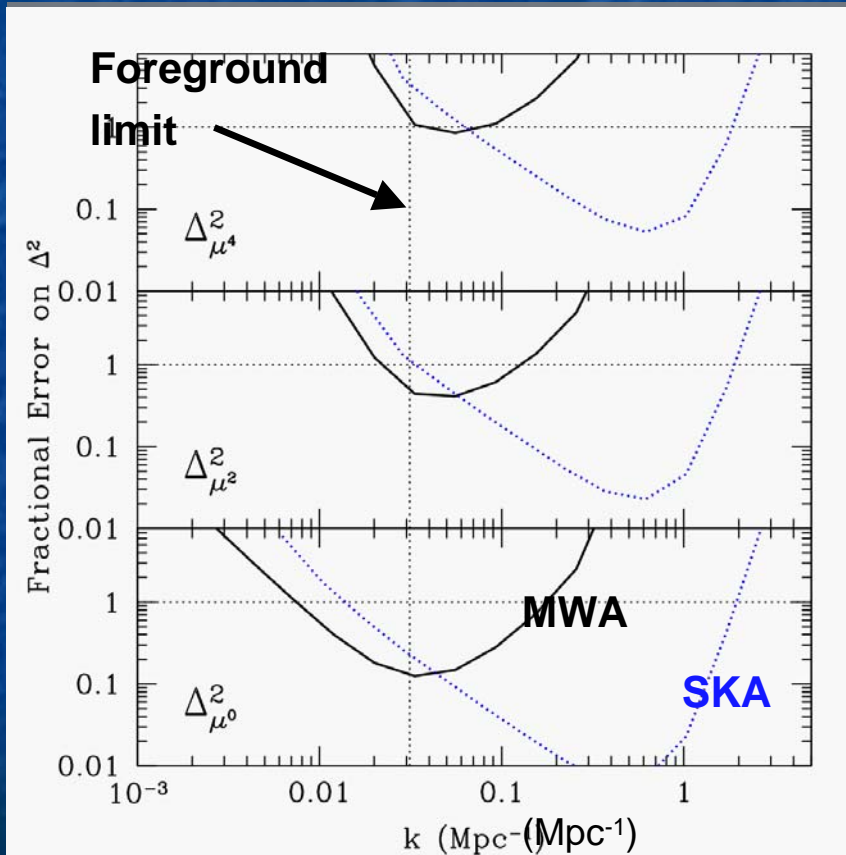
Future Directions III

- 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



Anisotropies in the Signal



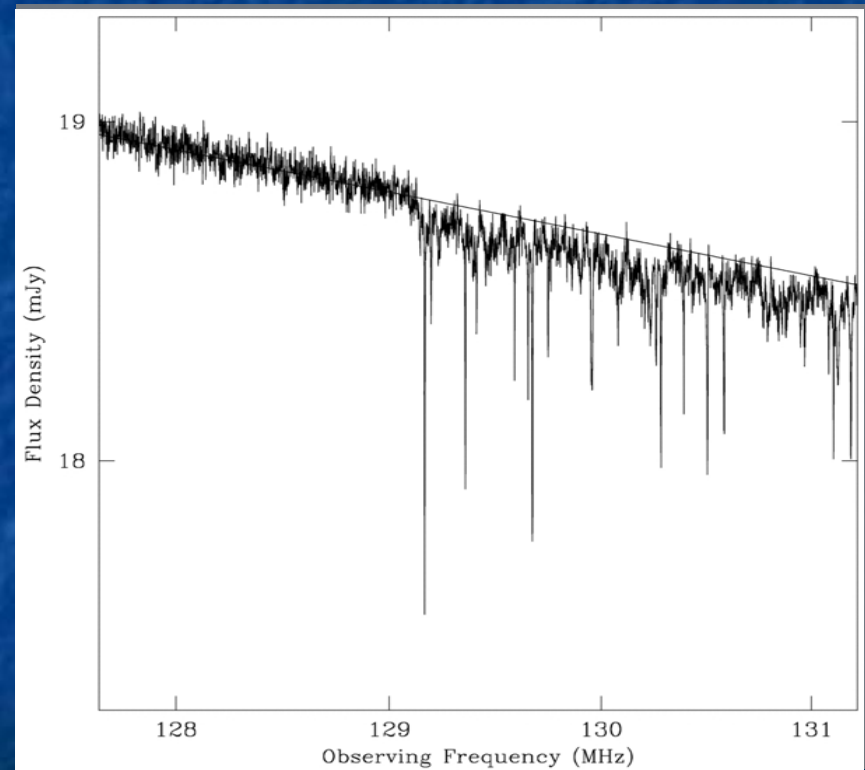
- Survey parameters
 - $\bar{z}=8$
 - $T_{\text{sys}}=440 \text{ K}$
 - $t_{\text{int}}=1000 \text{ hr}$
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- LOFAR very close to MWA

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)

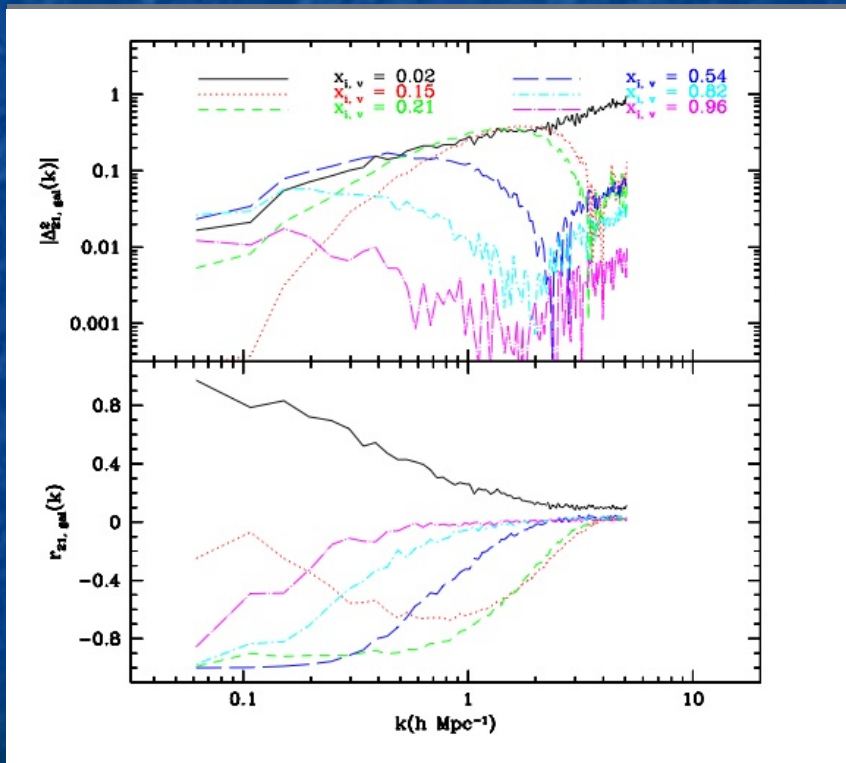
Future Directions V

- 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



Lidz, Zahn, & Furlanetto (in prep)

- 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?

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?!?