

Status of Foreground and Instrument Challenges for 21cm EoR experiments – Design and Analysis Strategies for SKA and HERA

Nithyanandan Thyagarajan (or just “Nithya”)

Jansky fellow at NRAO (Socorro)

Formerly at ASU

HERA+

MWA+

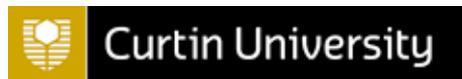
HERA Collaboration



MWA Collaboration



Raman Research Institute
Bangalore



International Centre for
Radio Astronomy Research

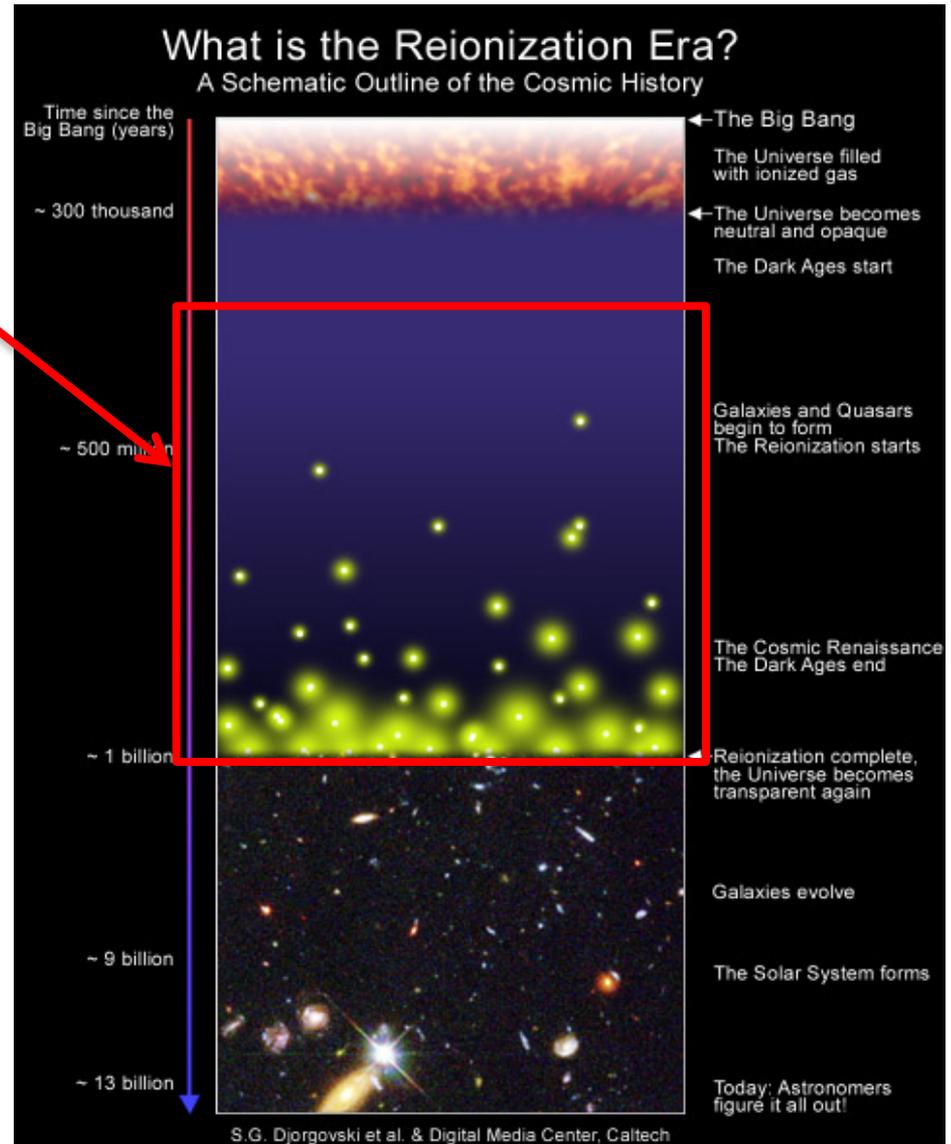


PERTH OBSERVATORY

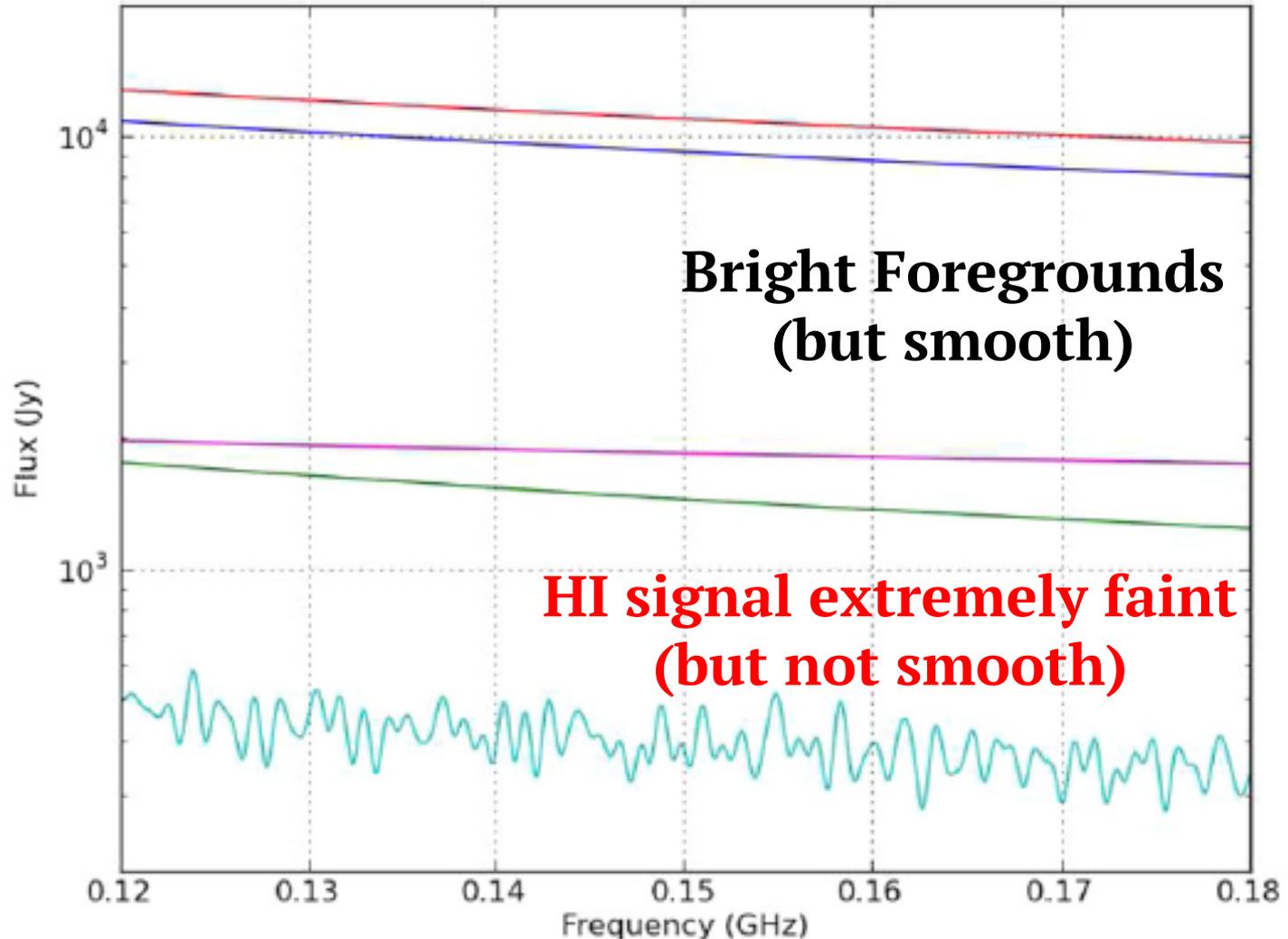


Why low frequency radio astronomy?

- Early Universe: dark ages, first stars and galaxies, EoR, large scale structure

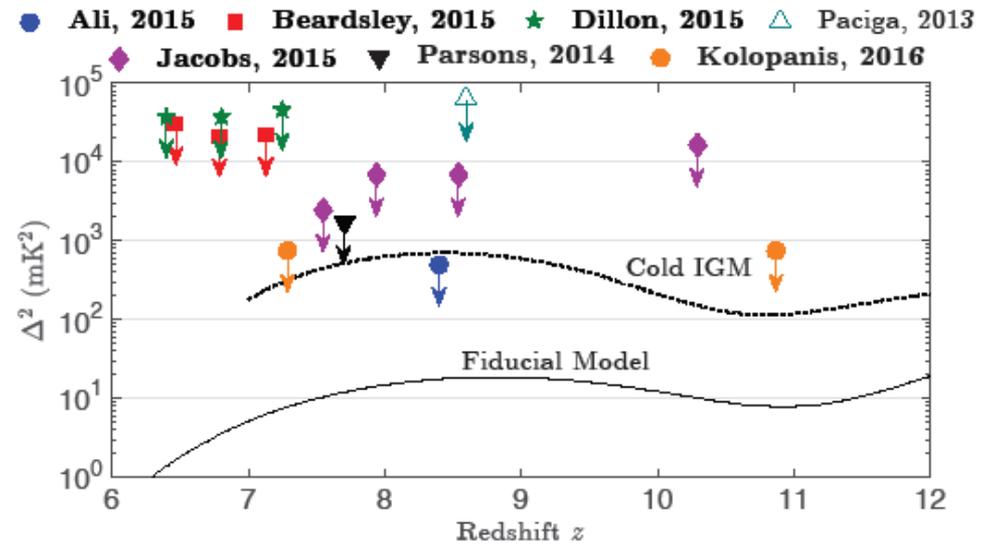
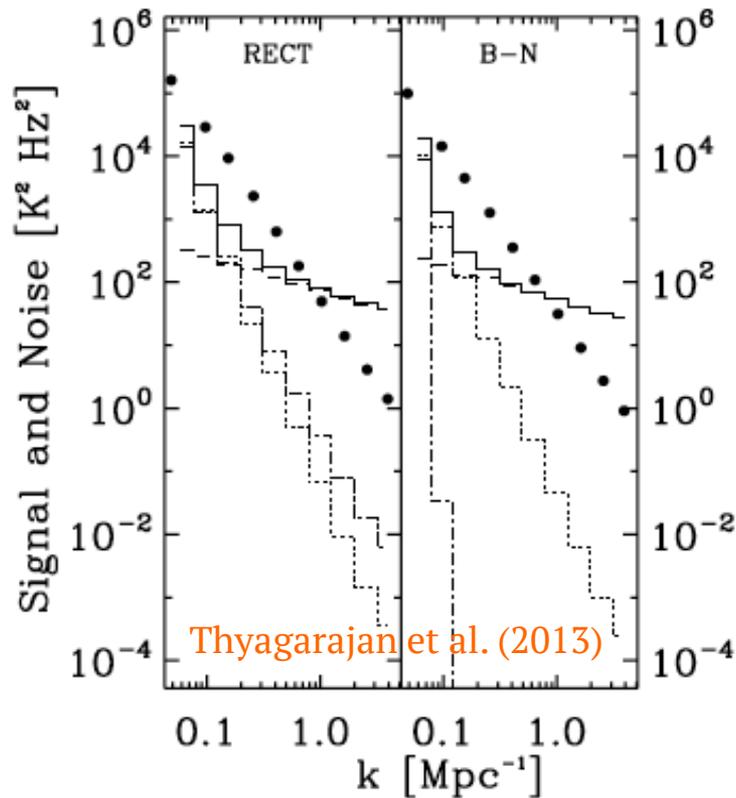


The Foreground Problem



Parsons et al. (2012)

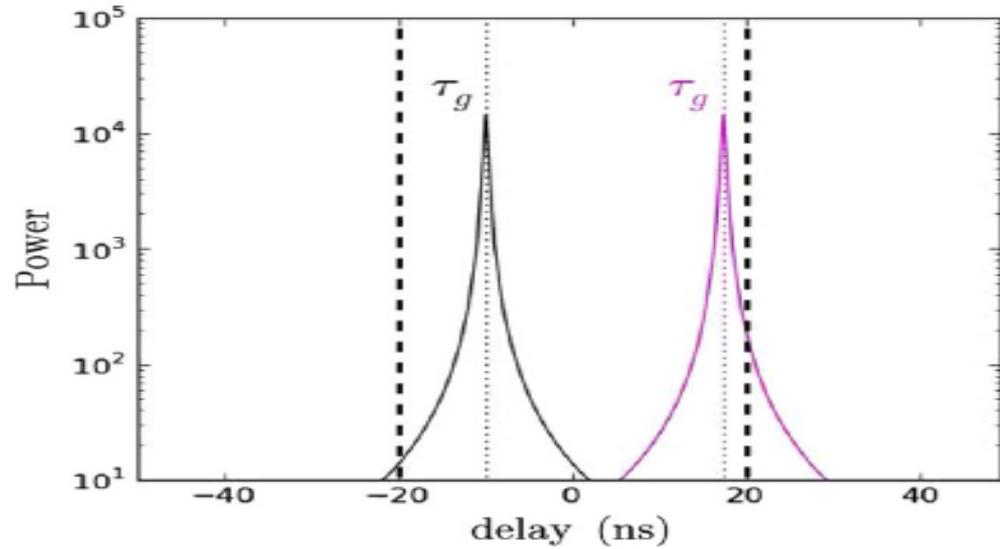
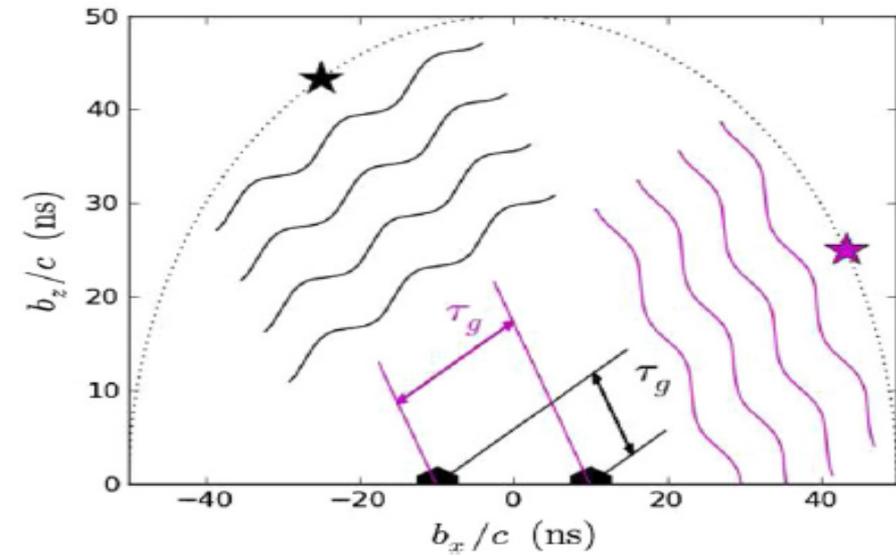
Expectations and Results from First-generation



Credit: Matt Kolopanis

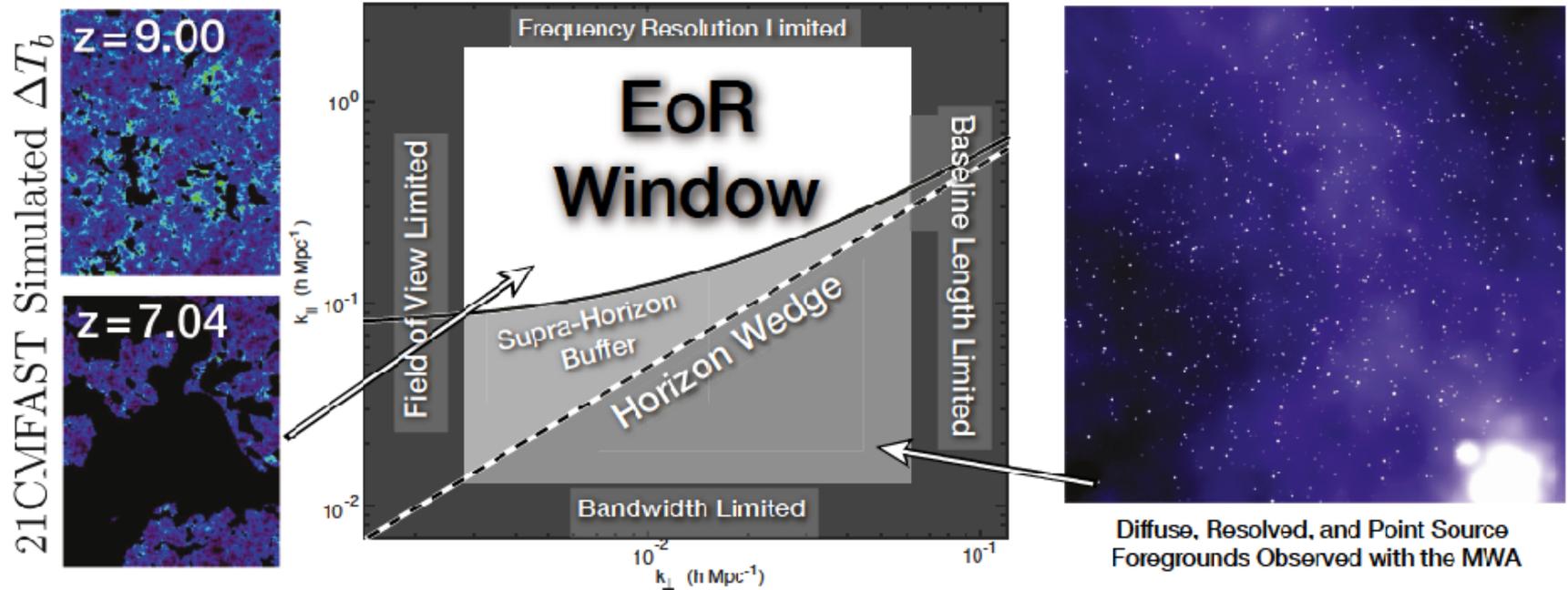
- >10 -sigma statistical detection expected with ~ 1000 hours data
- Currently limited by foregrounds and instrument systematics (e.g. PAPER64 - Ali et al. 2015, Pober et al. 2015; MWA - Dillon et al. 2013, Beardsley et al. 2016, Patil et al. 2017)

Fourier Space and Delay Spectrum

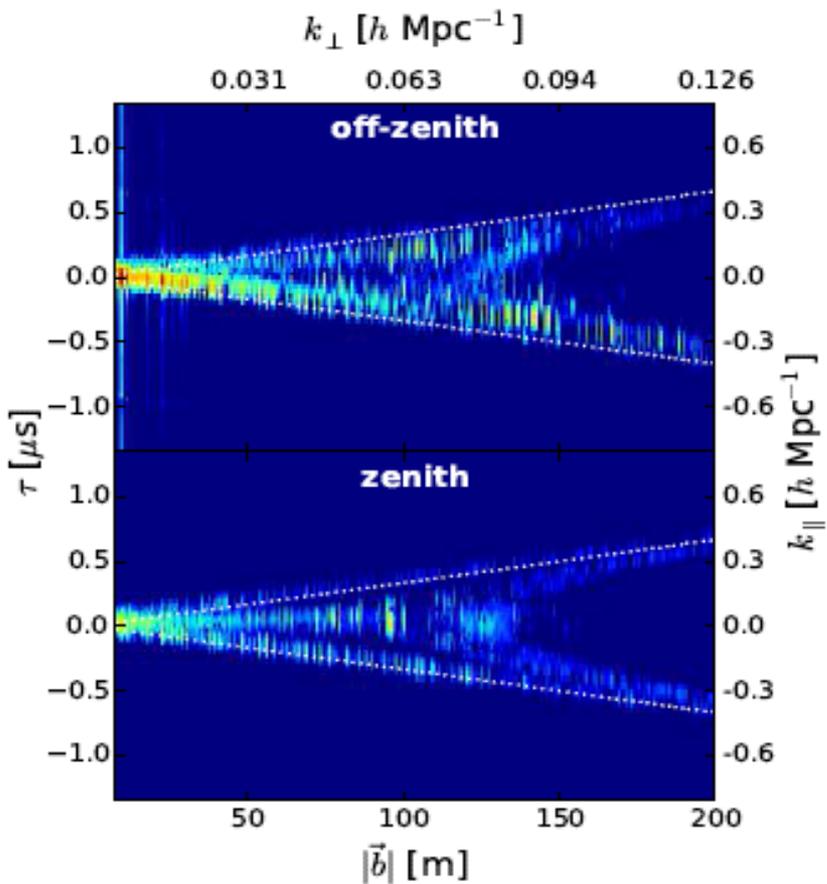


Parsons et al. (2012)

Foreground “Wedge” and EoR window

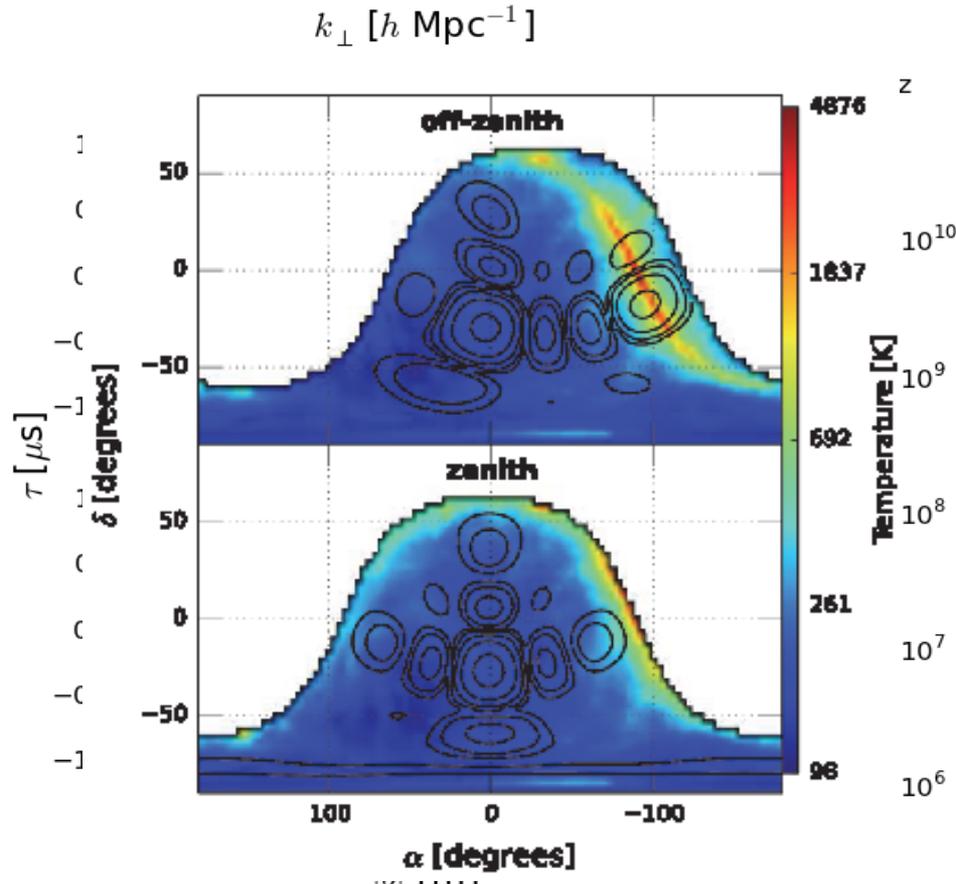


Impact of Wide-Field Foregrounds



Diffuse Emission

Thyagarajan et al. (2015a)



Point sources

The “Pitchfork” effect

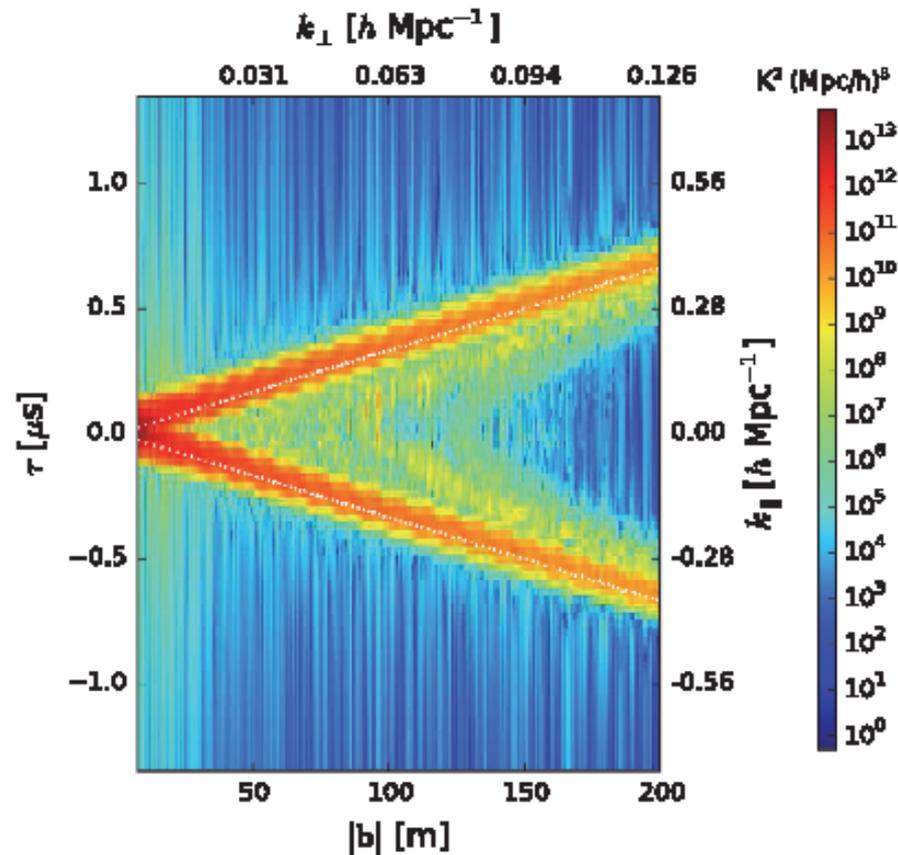
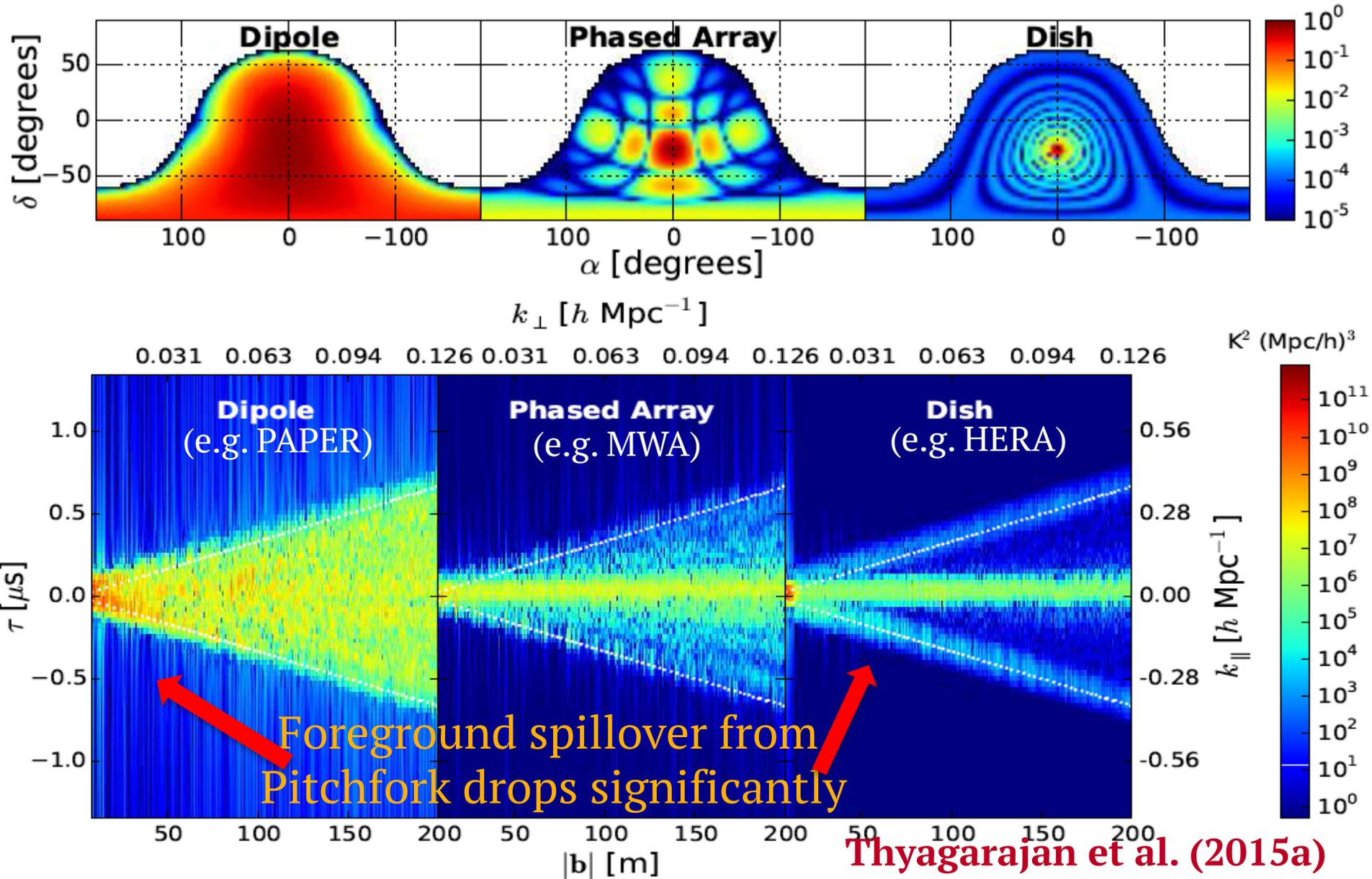


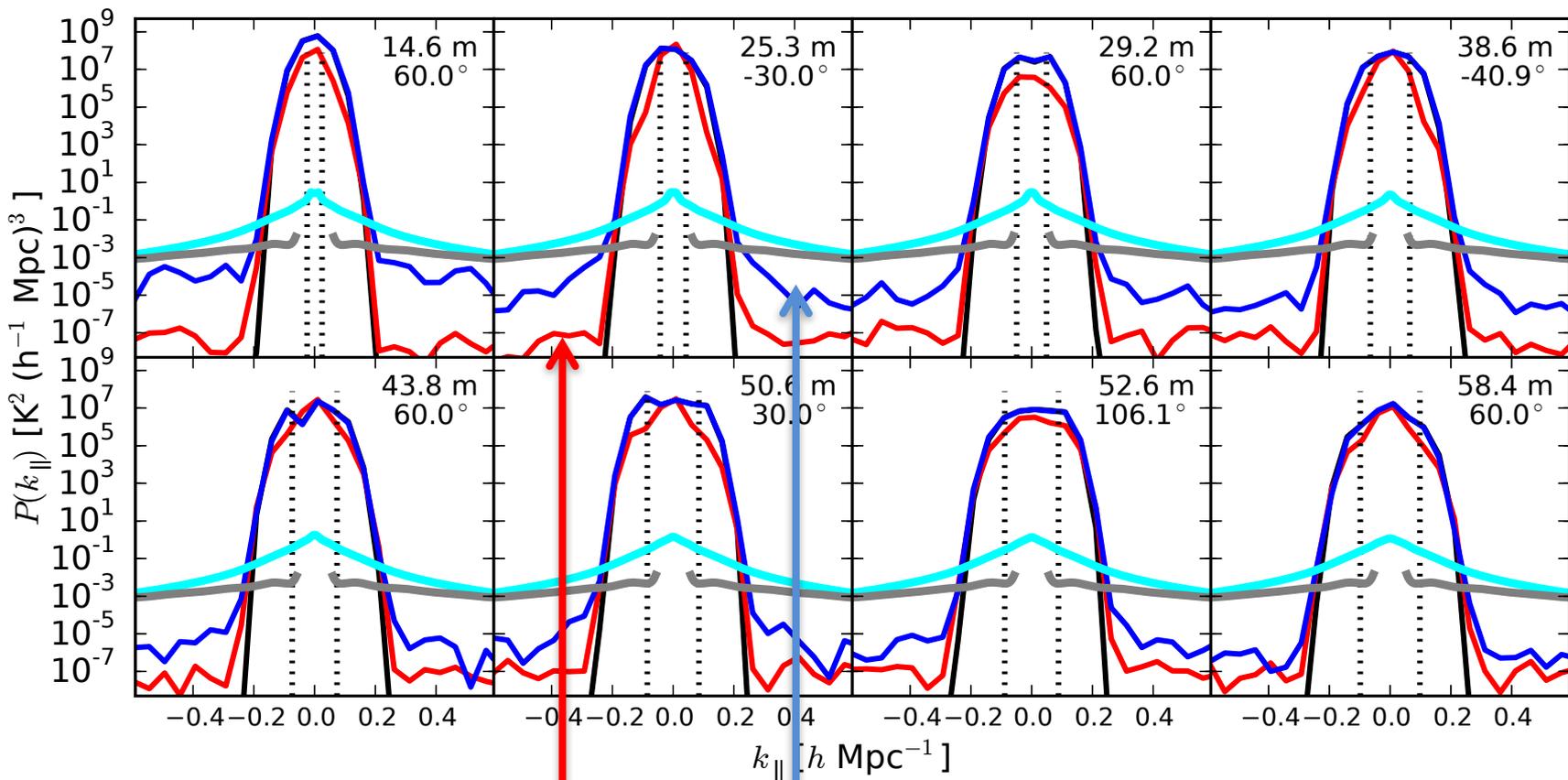
Figure 2. Wide-field effects on delay power spectra produced with a uniform sky brightness distribution measured by antenna pairs with a uniform power pattern across the visible hemisphere. Delay power spectra are obtained using Equations (1), (2), and (4) for each baseline, which are then stacked by baseline length. The axes correspond to cosmological dimensions. The non-zero response of the interferometer array to a uniform brightness distribution and the prominent *edge brightening* close to the horizon delay limits are wide-field effects. These are prevalent on all antenna spacings and are generic to all instruments used in wide-field measurements.

Thyagarajan et al. 2015a,b

Mitigation of systematics via Aperture Shape



Effects of Beam Chromaticity



Thyagarajan et al. (2016)

Uniform Disk Airy Pattern

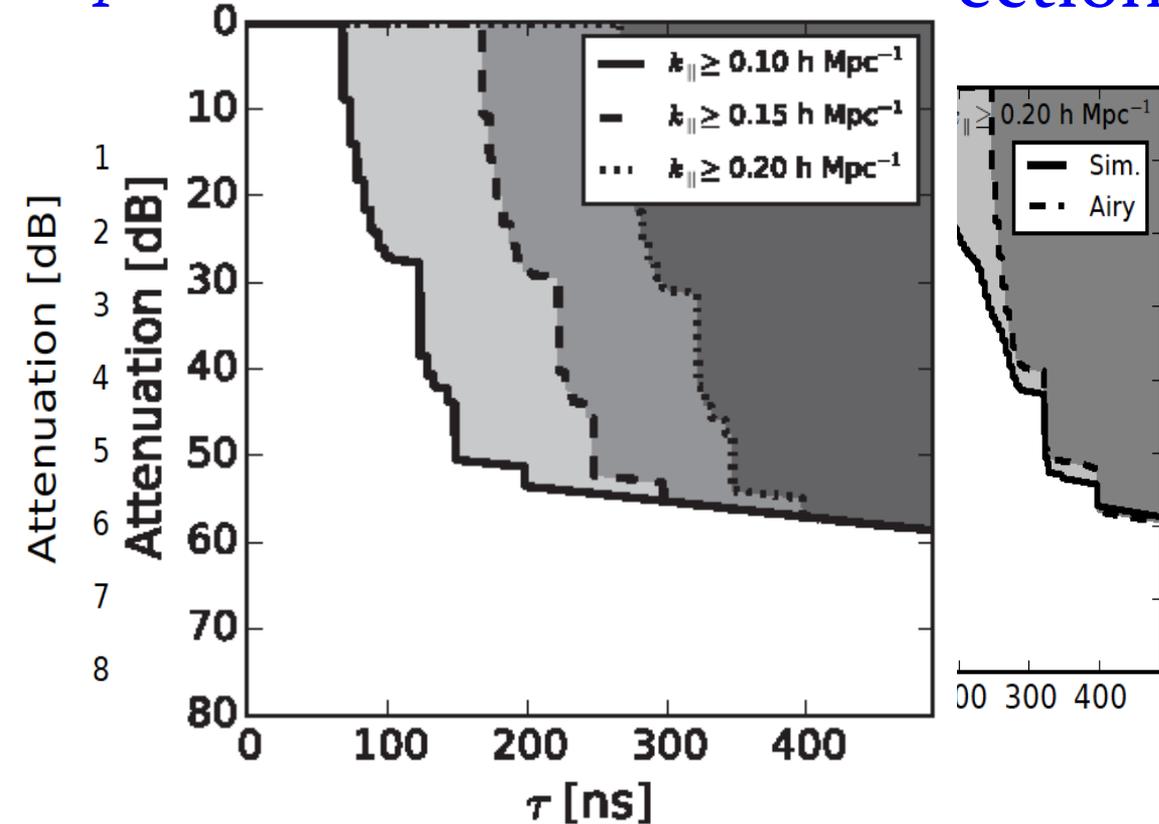
Simulated Chromatic HERA beam

- Differences seen only due to spectral differences in Antenna beam
- Beam chromaticity worsens foreground contamination
- HERA aiming for such a robust element design

Delays from Geometrical and Electrical Reflections

Design Specs on Reflections in Instrument

Dish-Feed Reflections Antenna-to-Antenna Reflections

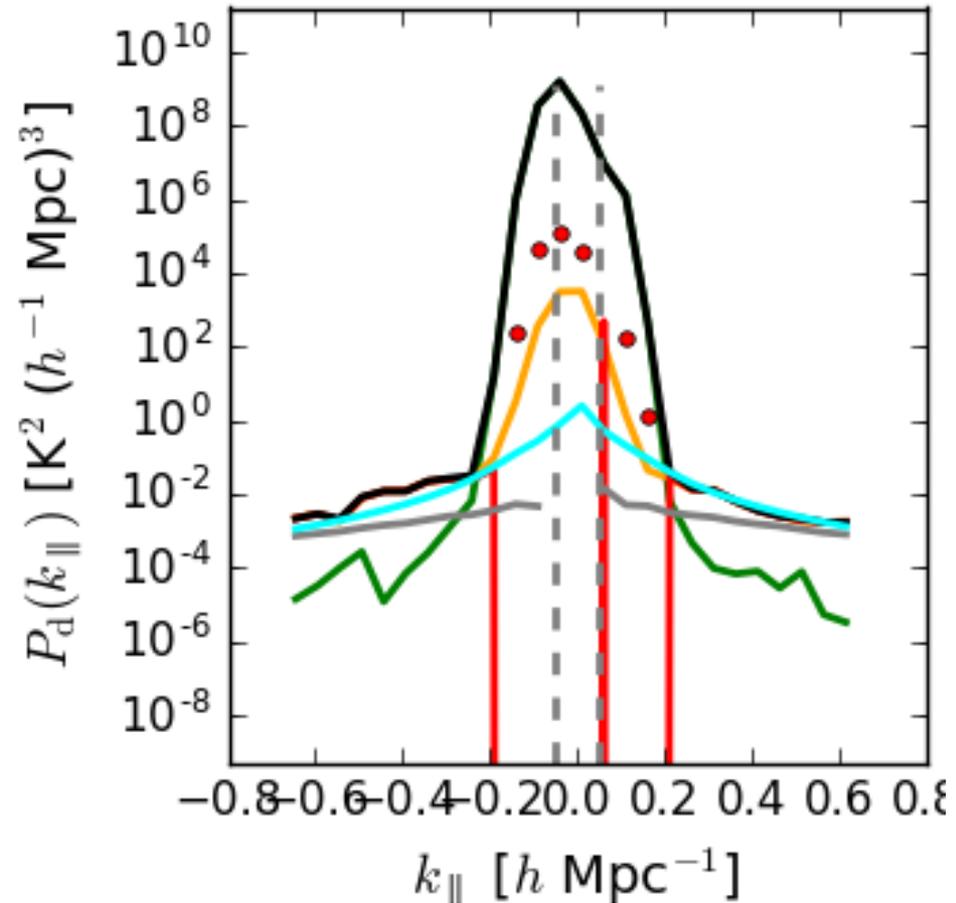
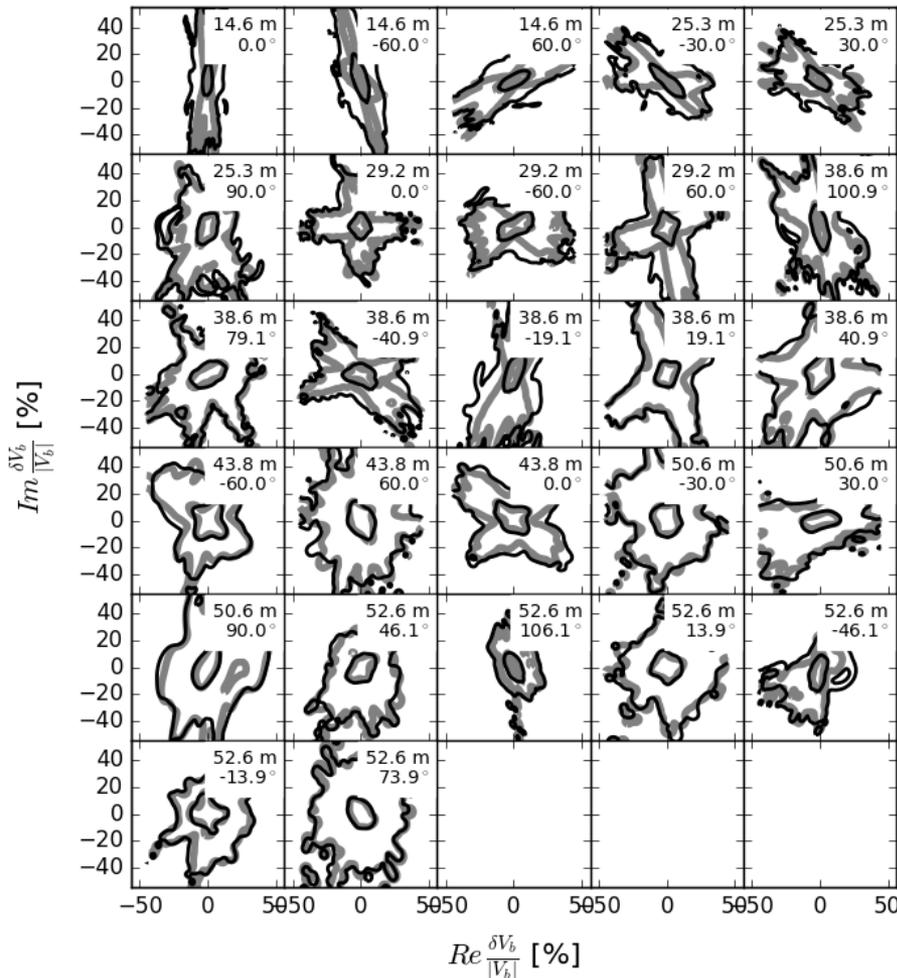


- Reflections inevitable in electrical systems
- Reflections extend foregrounds and contamination in delay spectrum
- Require reflected foregrounds to be below HI signal levels
- HERA will aim for these specs
- Similar study is ongoing for SKA (with de Lera Acedo et al., Cambridge)

Thyagarajan et al. (2016)
Ewall-Wice et al. (2016)
Neben et al. (2016)
Patra et al. (2016)
DeBeor et al. (2016)

Effects of Antenna Position Errors

Thyagarajan et al. (in prep.)



Deviation from redundancy quickly introduce undesirable levels of spectral structure

Time to walk the talk with 21cm EoR experiments

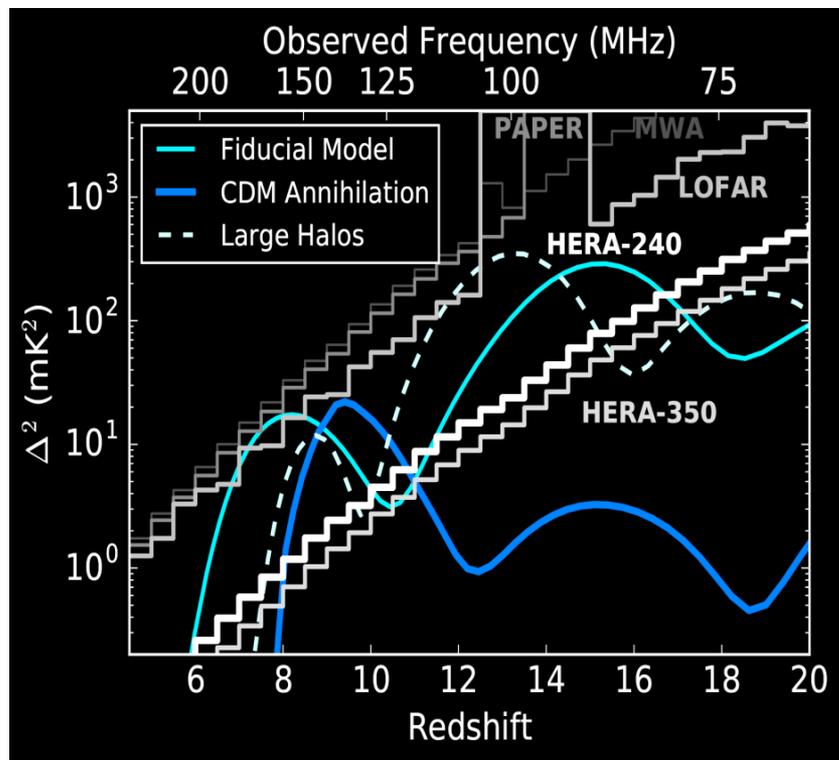
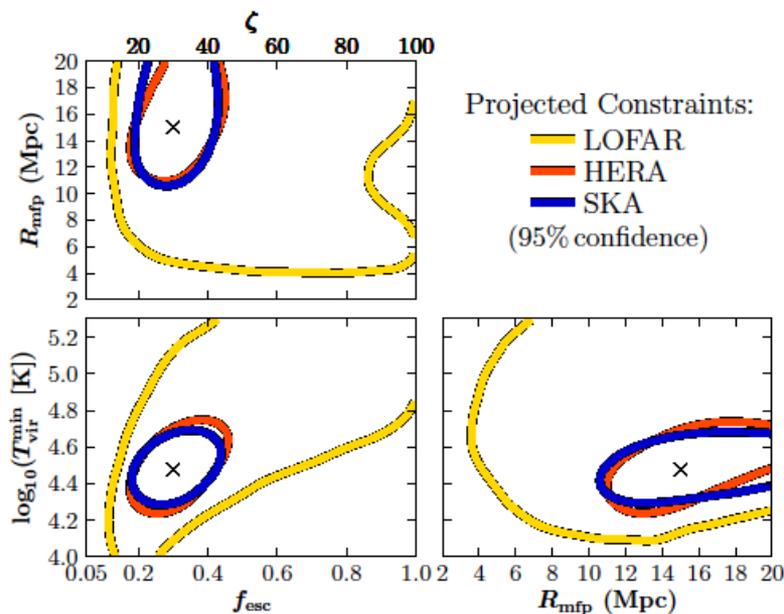
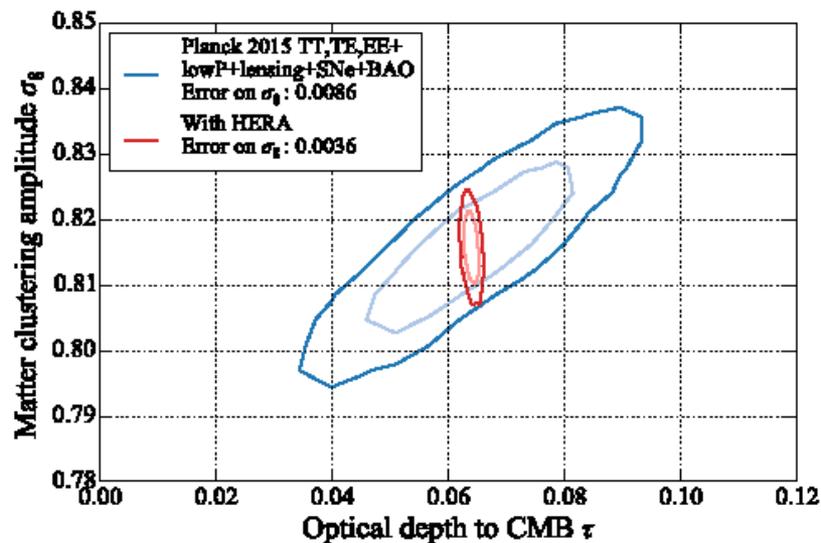


Fig. 3.— 1σ thermal noise errors on $\Delta^2(k)$, the 21 cm power spectrum, at $k=0.2 h \text{ Mpc}^{-1}$ (the dominant error at that k) with 1080 hours of integration (black) compared with various heating and reionization models (colored).



Greig & Mesinger (2015)



Courtesy: Adrian Liu

Challenges

- Knowledge and behaviour of foregrounds – point sources and diffuse emission
- Control of wide-field “pitchfork” effects
- Careful aperture design
- Control of antenna beam chromaticity
- Control of reflections in instrument
- Control of antenna positions
- Careful system design

And more challenges

- Calibration Accuracy
- Precise Instrument Design & Knowledge
- Polarization Leakage compounded with wide-field effects?
- Recombination lines taken lightly?
- Antenna-to-antenna variations in beam and signal path?
- Over-reliance on few analysis techniques?
- Cross-correlation with other approaches including at higher frequencies

Summary

- Systematics are the biggest challenge to EoR and low frequency experiments - HERA, SKA, MWA, PAPER, LOFAR
- Best solutions are via robust instrument design
- PRISim – high precision simulations for wide-field radio interferometry – publicly available:
<https://github.com/nithyanandan/PRISim>
- Discovery of new instrument + foreground physics:
 - Foregrounds + wide-field instruments leads to “pitchfork” contamination
 - Antenna beam chromaticity, reflections worsen contamination (thus requires careful design motivated cosmologically)
 - Control antenna position errors to preserve redundancy
 - Used in HERA design
 - SKA design also under study