# Connecting 21 cm Observations to Theoretical Models

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NSF Postdoctoral Fellow
Brown University

Preparing for the 21 cm Revolution
October 2, 2015

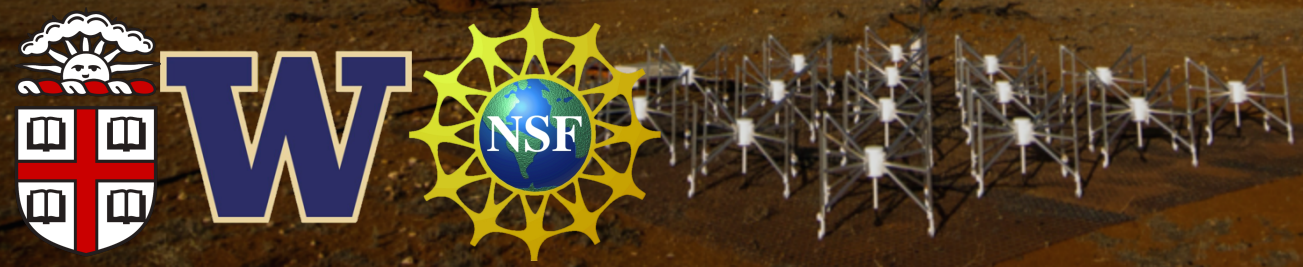


Photo Credit: Peter Wheeler, ICRAR

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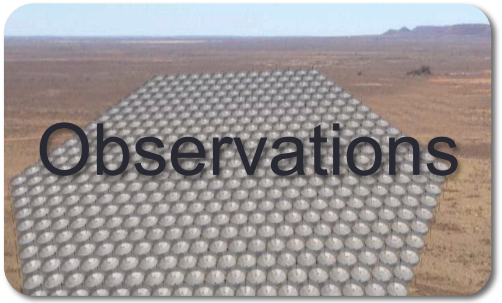


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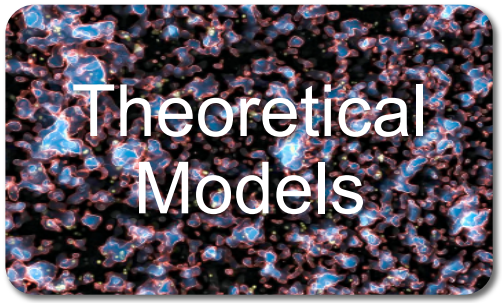

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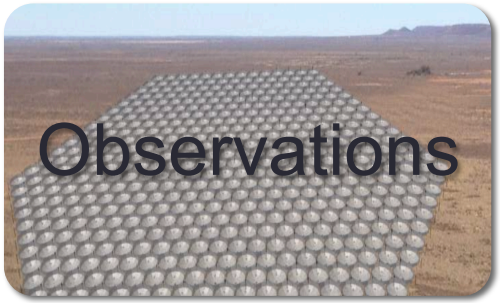


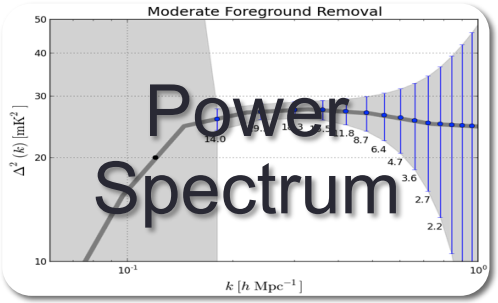


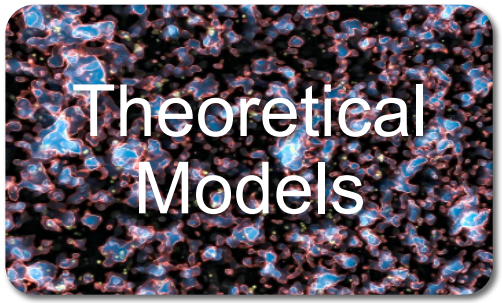

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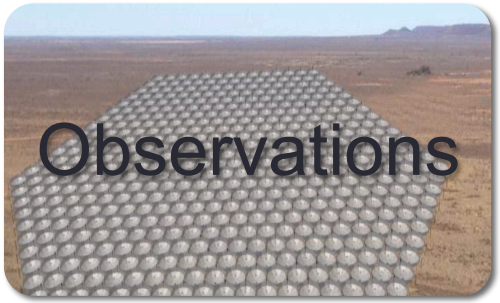
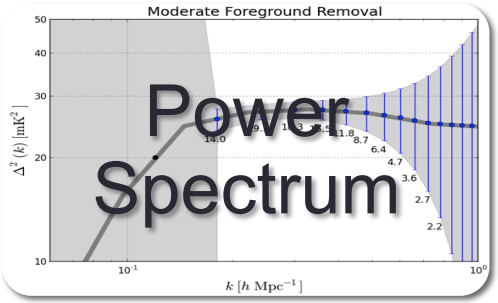
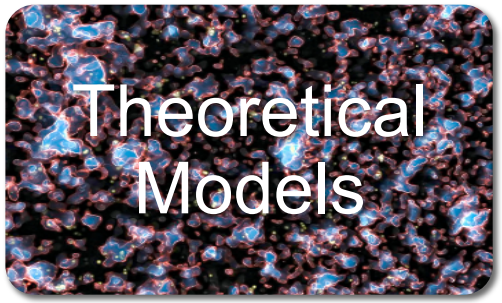


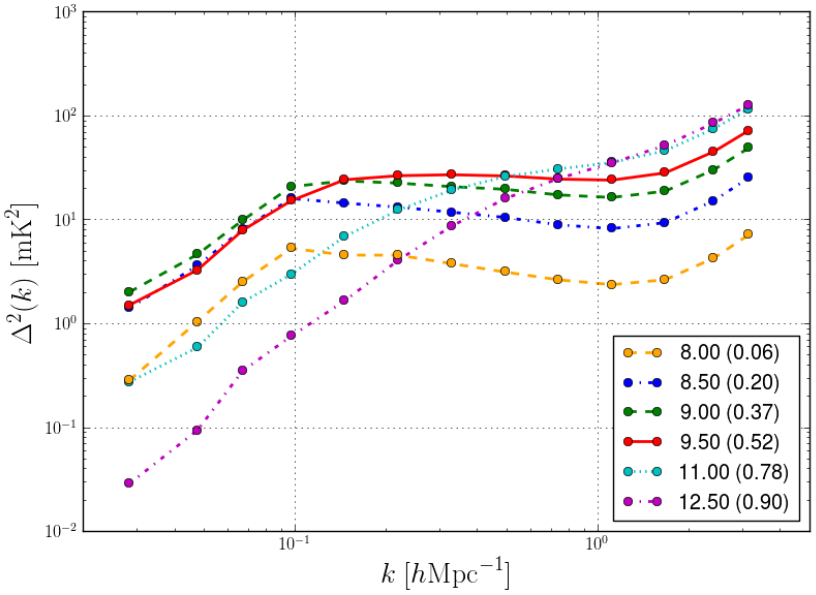



# So You Want To Constrain Some Theory

## Real Space

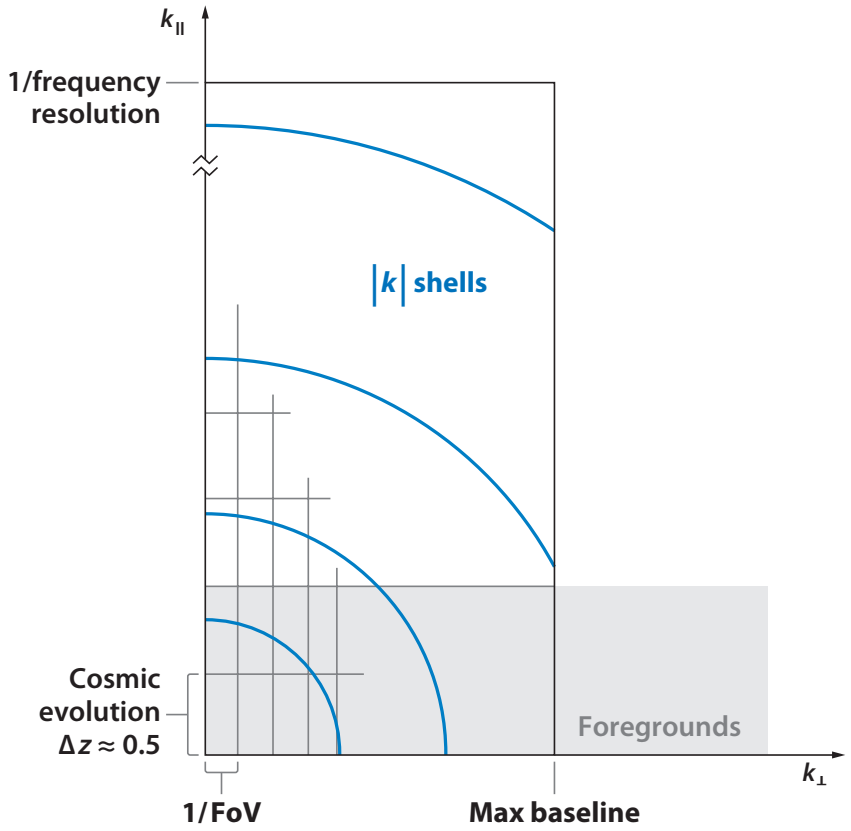
## Power Spectrum



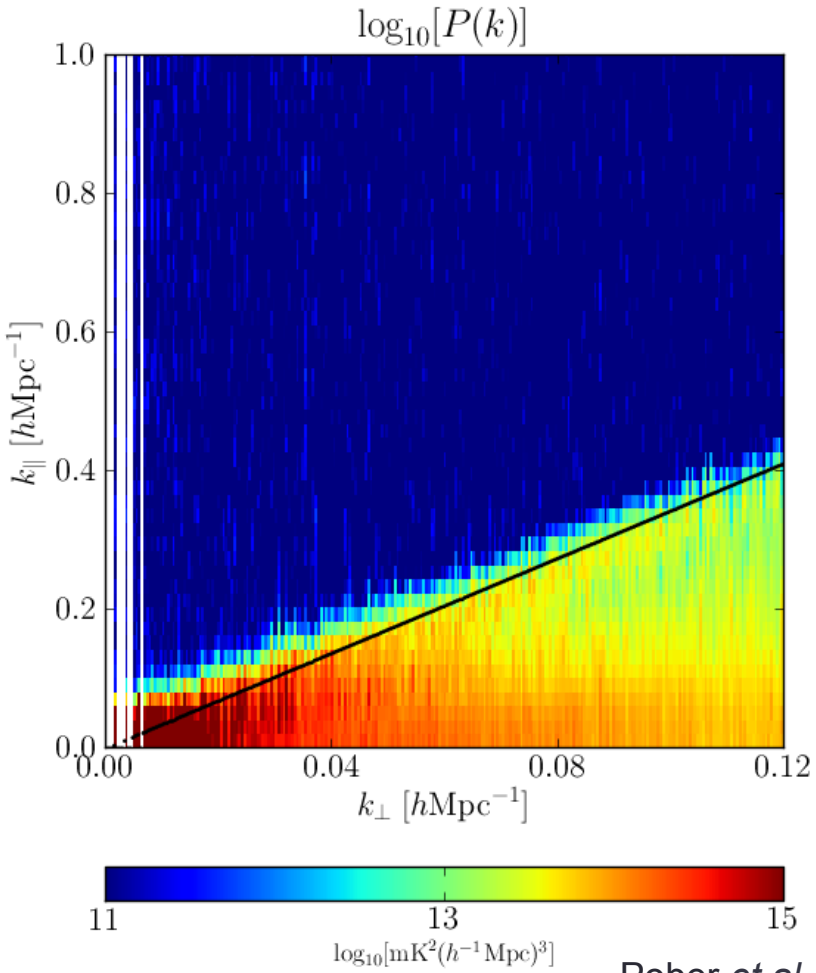

Pober et al. (2014)

# Foregrounds: Theory and Practice

## Predicted




## Observed

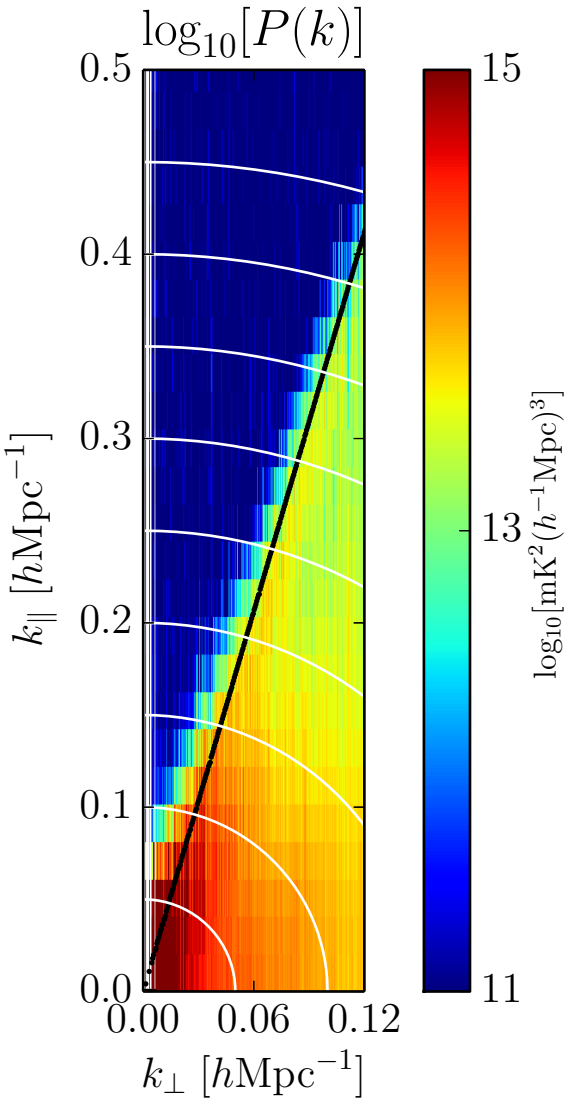



Morales & Wyithe 2010

Pober *et al.* 2013

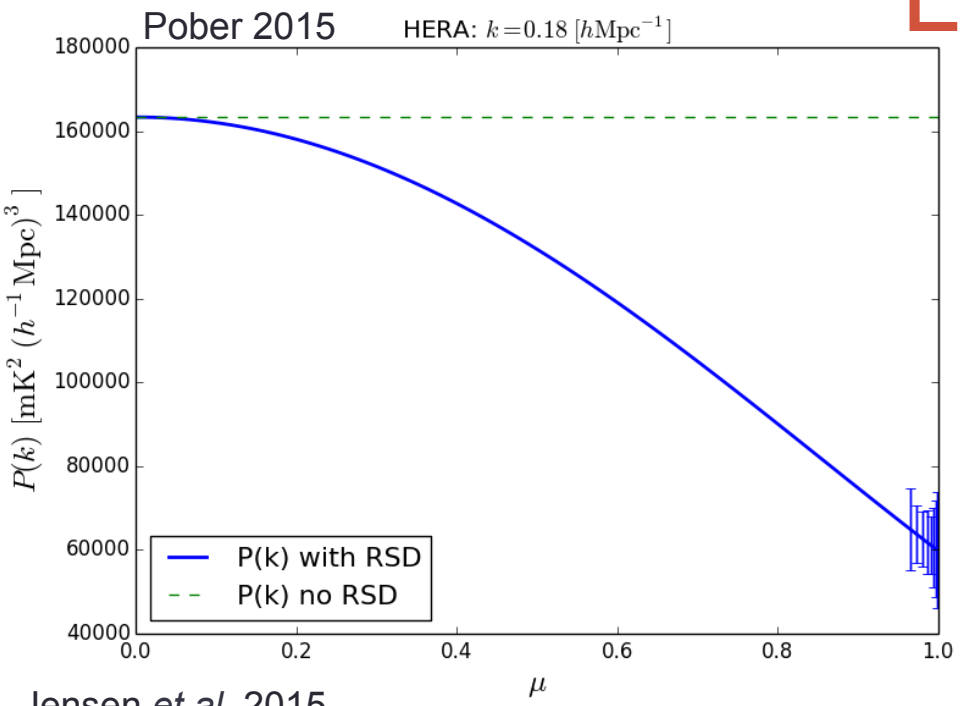
# The Wedge (To Scale)

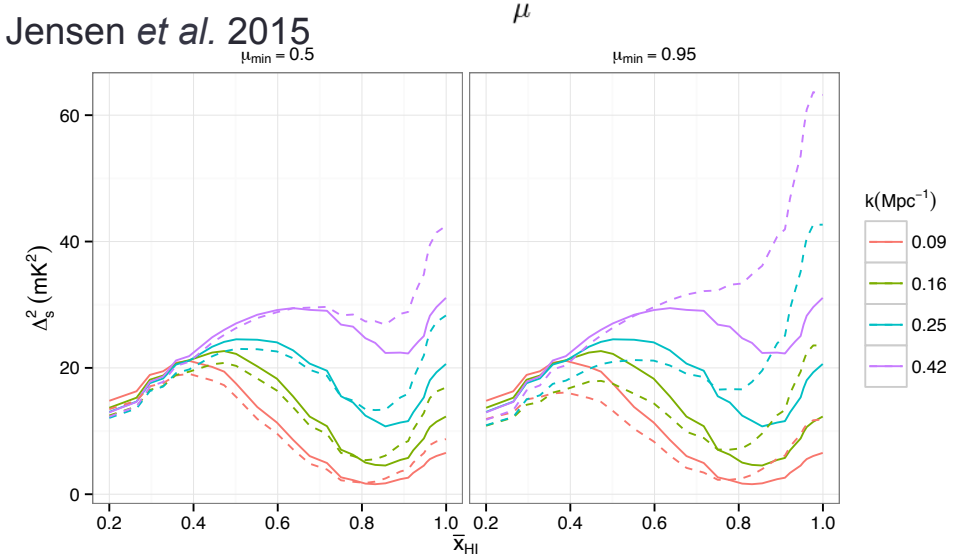
- Real instruments do not probe $k_{||}$ and $k_{\perp}$ on equal scales
  - 100 kHz resolution ➔ $k_{||,max}$ ~ 5 h/Mpc
  - 300 m baseline ➔ $k_{\perp,max}$ ~ 0.15 h/Mpc
- 21 cm experiments probe line of sight *k* modes
- Wedge exacerbates issue




Pober 2015

# Line of Sight Modes




- Observed power spectrum is in *redshift space* – not isotropic
- Anti-correlation between density and ionization fields can *decrease* line of sight power
- Potential for “wedge” bias if not accounted for (Jensen *et al.* 2015)

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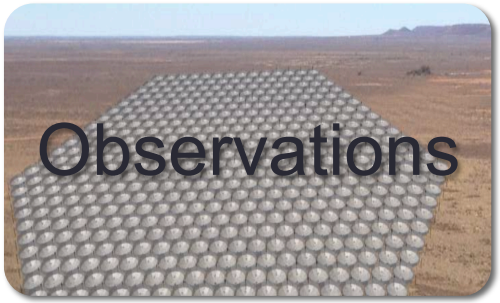
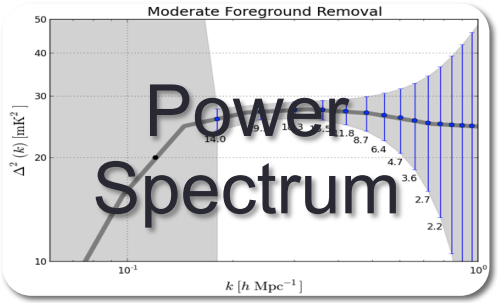
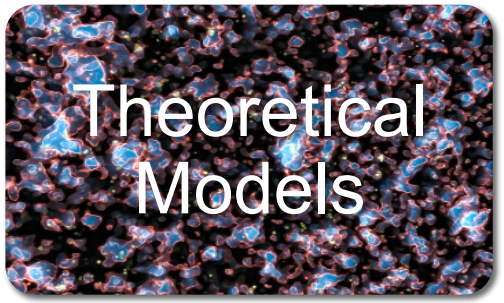
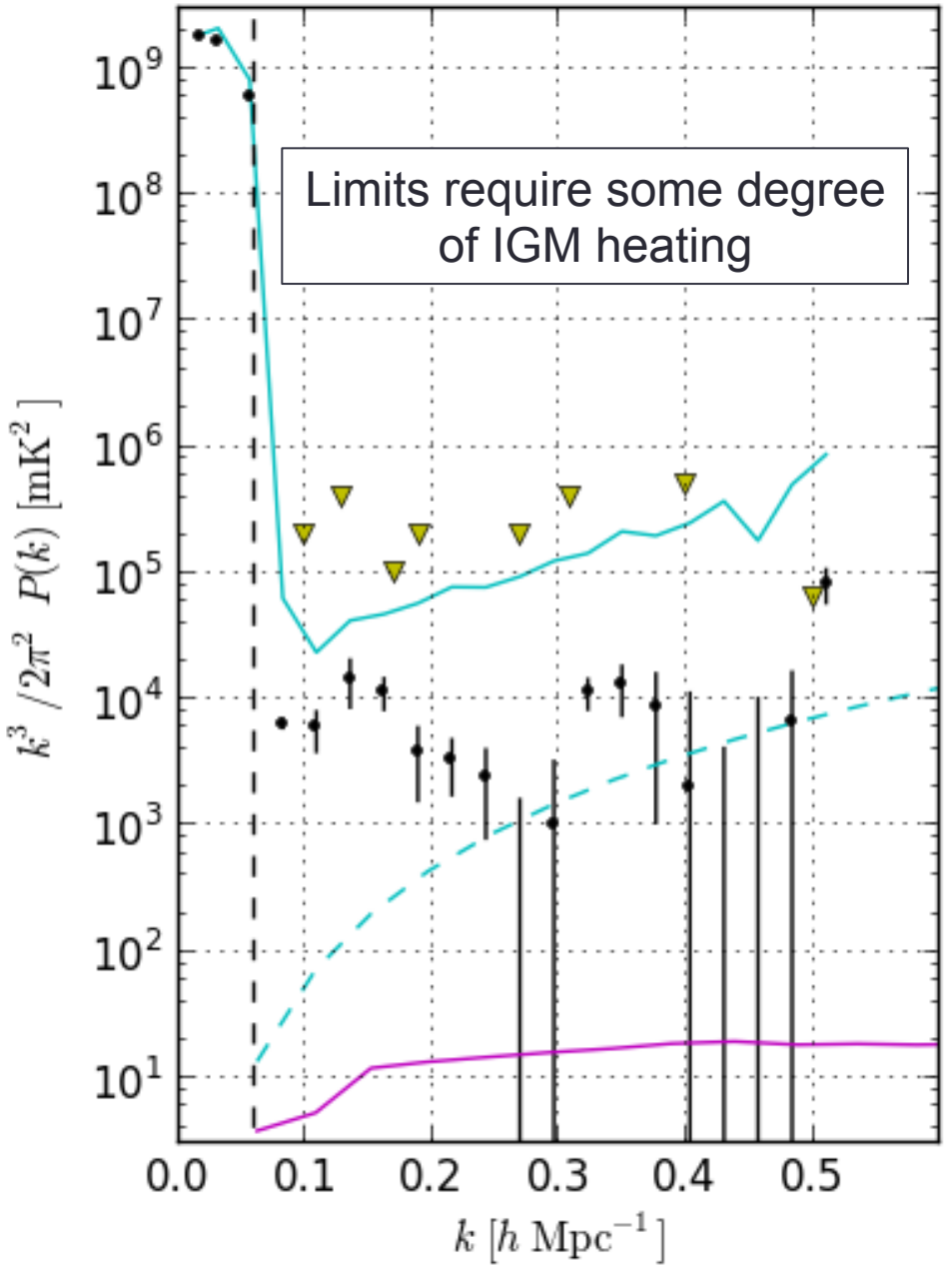


# Sensitivity Limits

- Parsons *et al.* 2014: $\Delta^2(k) < 1681\ mK^2$ ($z = 7.7$)



# Sensitivity Limits

- Parsons *et al.* 2014: $\Delta^2(k) < 1681\ \mathrm{mK}^2$ ($z = 7.7$)
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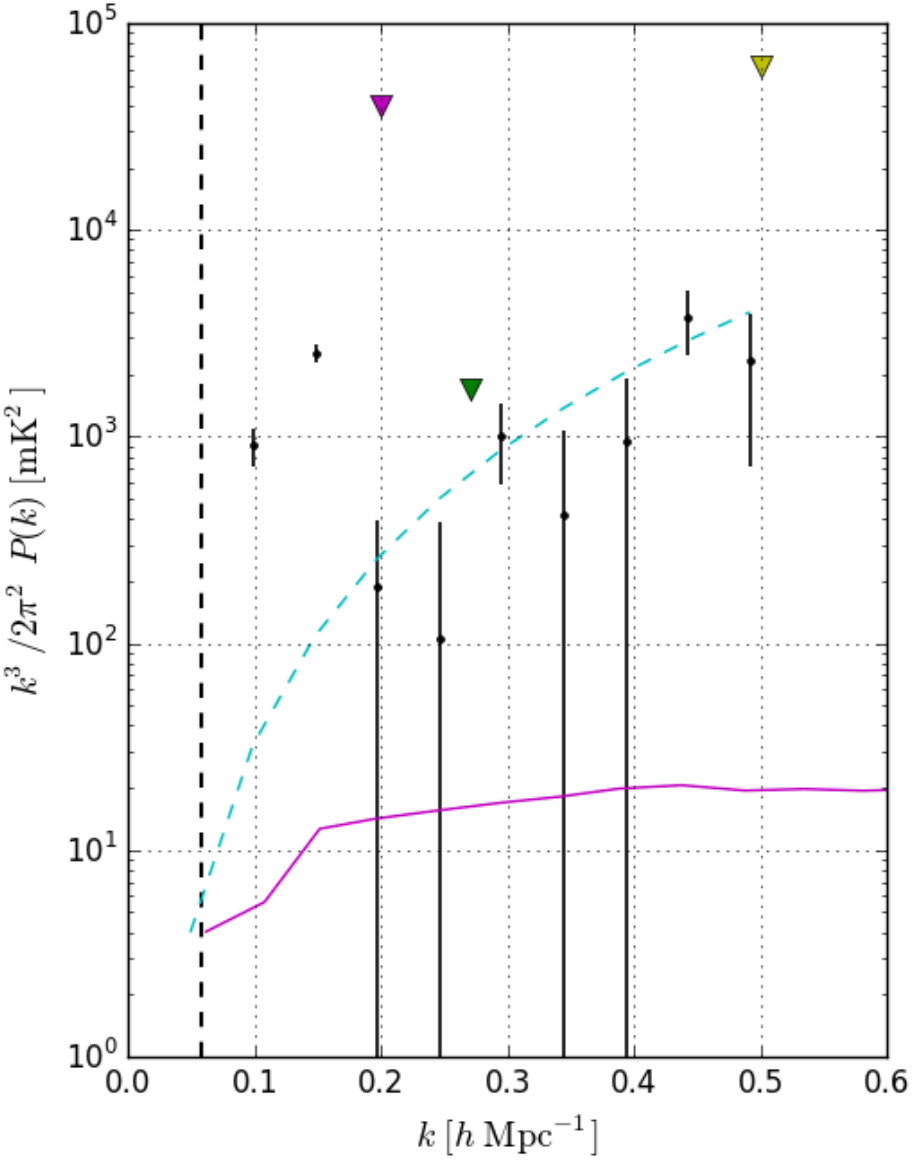
Ali *et al.* 2015



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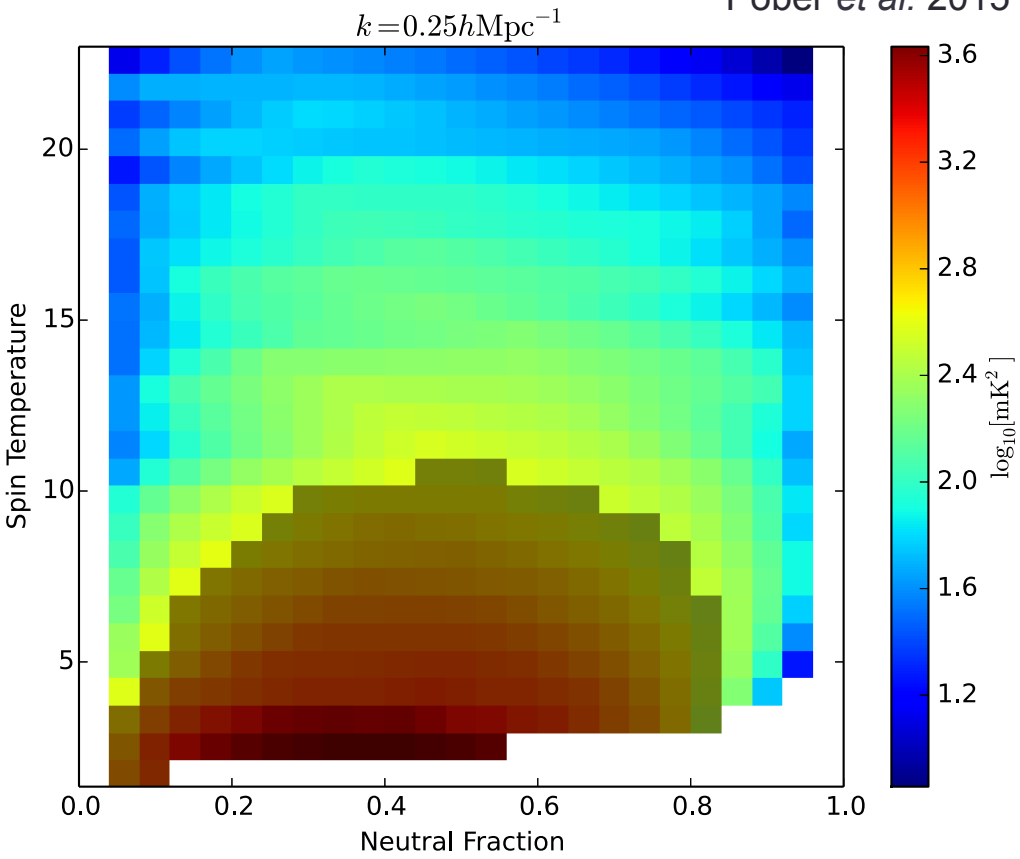


Quantitative limits on IGM temperature: $T_{spin} > 10$ K

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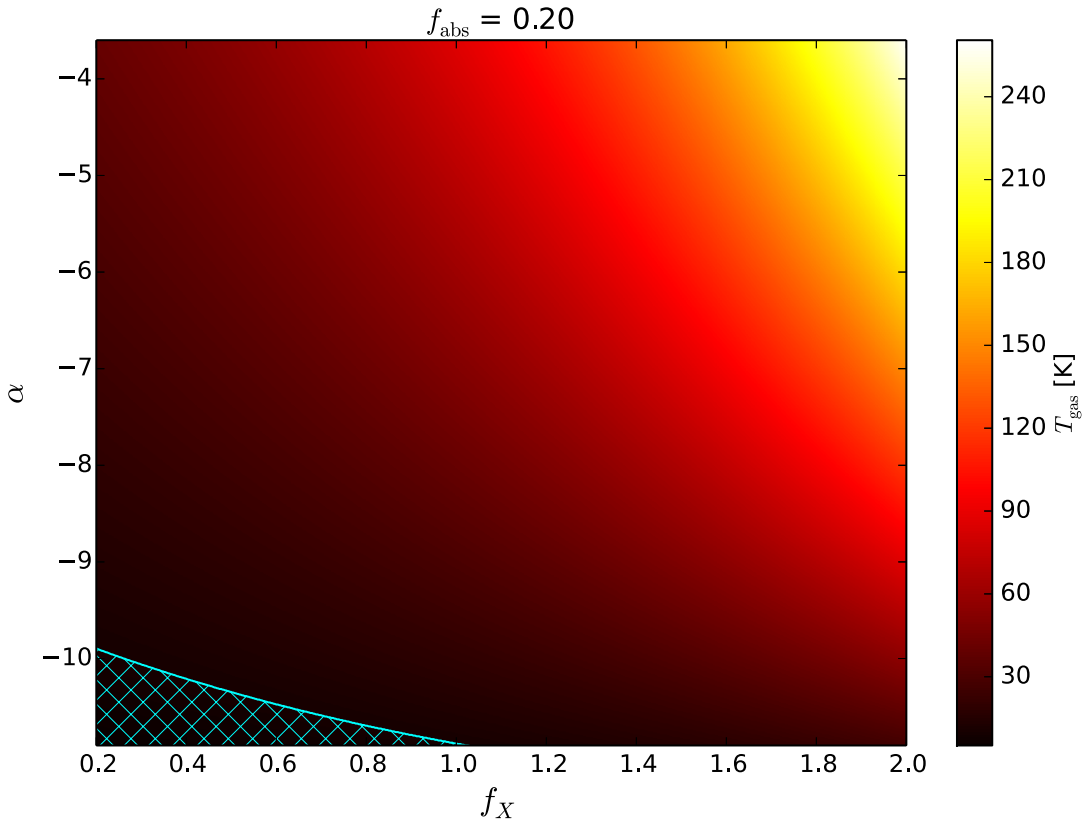


Potential that observed galaxies cannot heat IGM to level required

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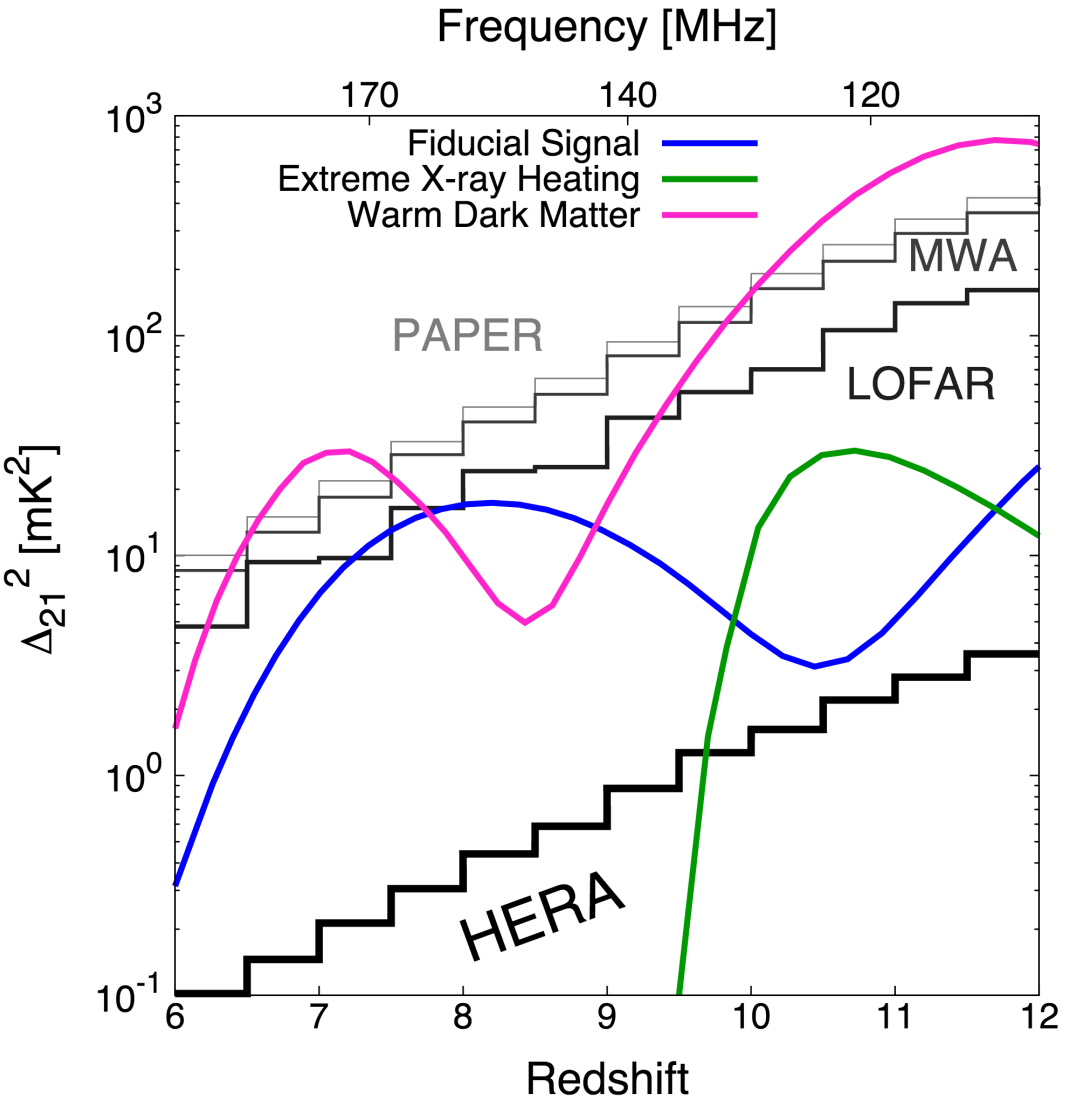
  $\Delta^2(k) \leq 1\ mK^2$




adapted from Mesinger, Ewall-Wice & Hewitt 2014

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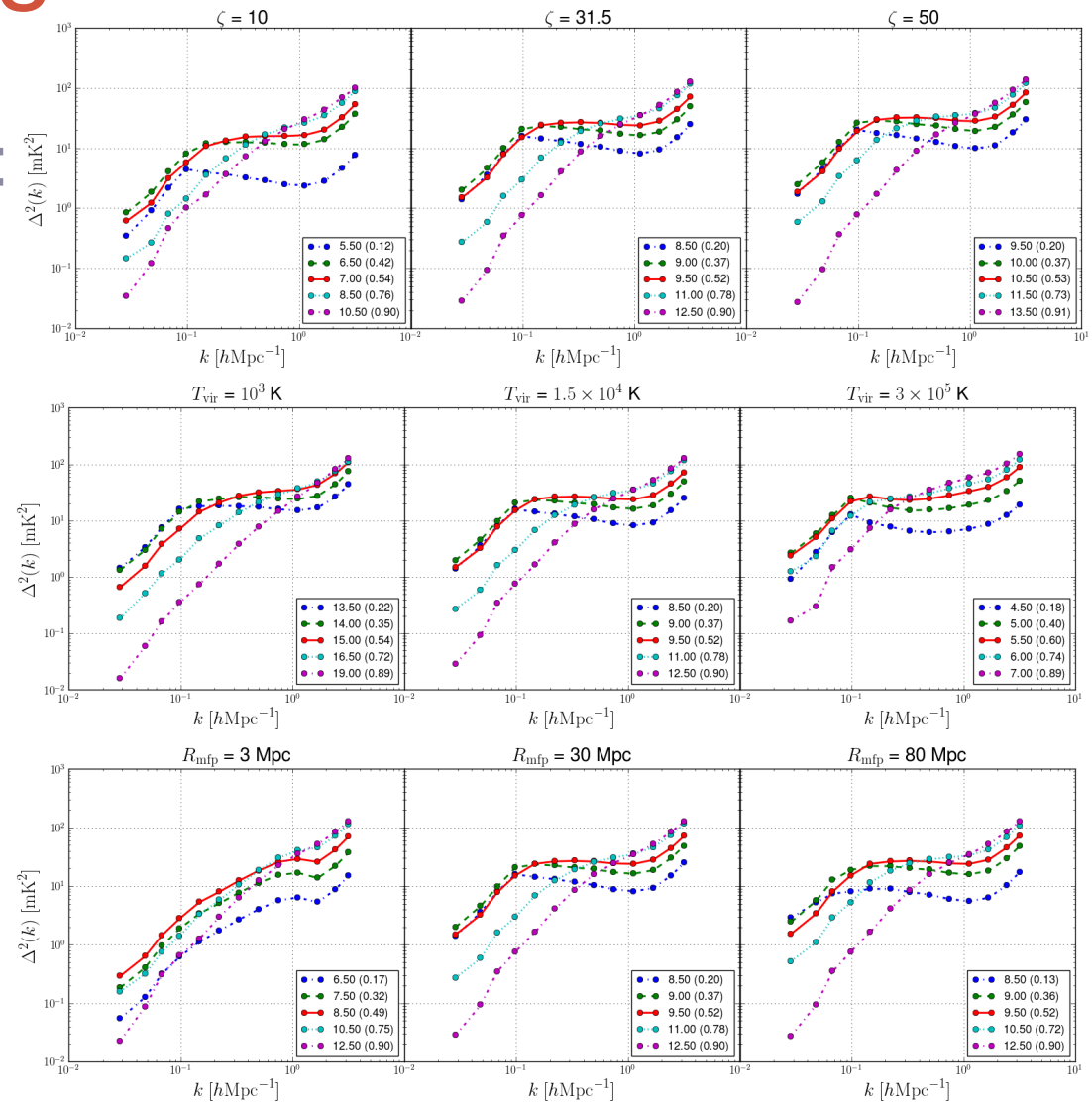

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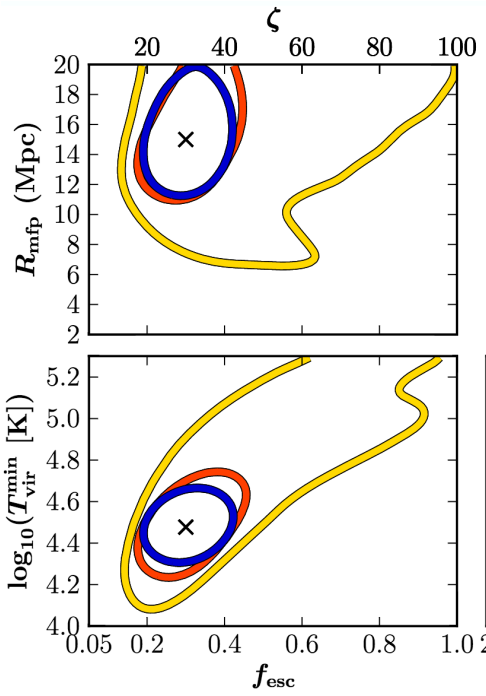


| Instrument (multi-$z$) | Parameter (% error) $\frac{\zeta}{\zeta_{fid}}$ | $\frac{R_{mfp}}{R_{fid,mfp}}$ | $\frac{\log_{10}(T_{vir}^{min})}{\log_{10}(T_{vir,fid}^{min})}$ |
|---|---|---|---|
| LOFAR | 1.32 (40.38) | 1.03 (20.06) | 1.05 (5.43) |
| HERA | 1.03 (11.81) | 1.00 (11.99) | 1.00 (1.95) |
| SKA | 1.02 (6.11) | 1.00 (10.04) | 1.00 (0.96) |

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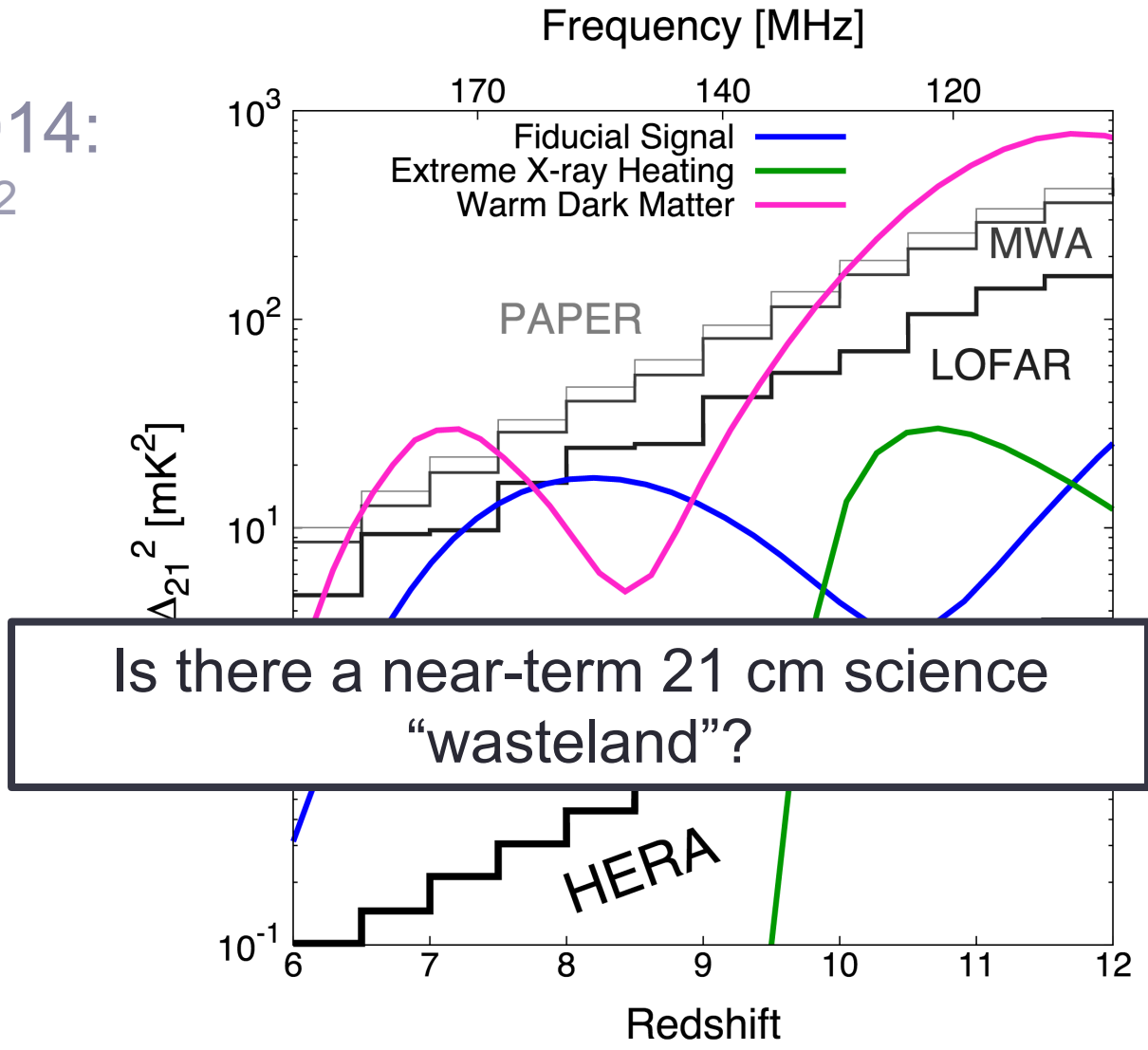
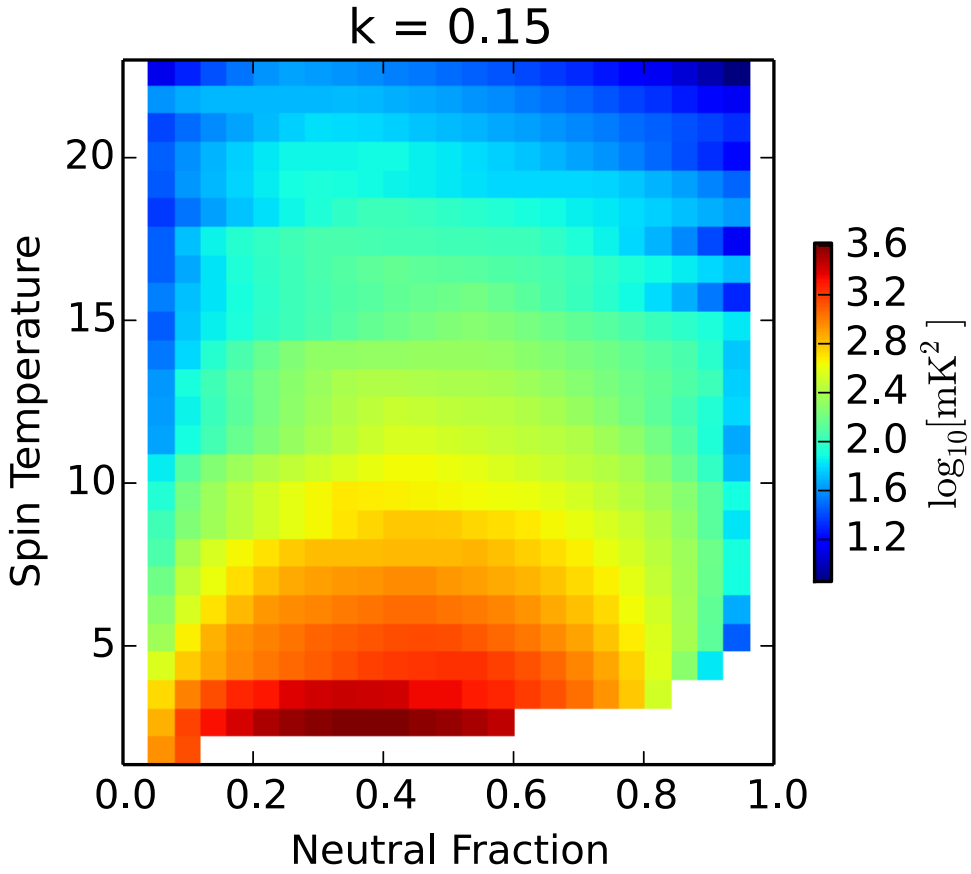



Is there a near-term 21 cm science "wasteland"?

adapted from Mesinger, Ewall-Wice & Hewitt 2014

# Intermediate Sensitivity Science

$$\delta T_b(\nu) \approx 9 x_{\rm HI}(1+\delta)(1+z)^{\frac{1}{2}} \left[1 - \frac{T_{\rm CMB}(z)}{T_S}\right] \left[\frac{H(z)/(1+z)}{{\rm d}v_\parallel/{\rm d}r_\parallel}\right] {\rm mK}$$

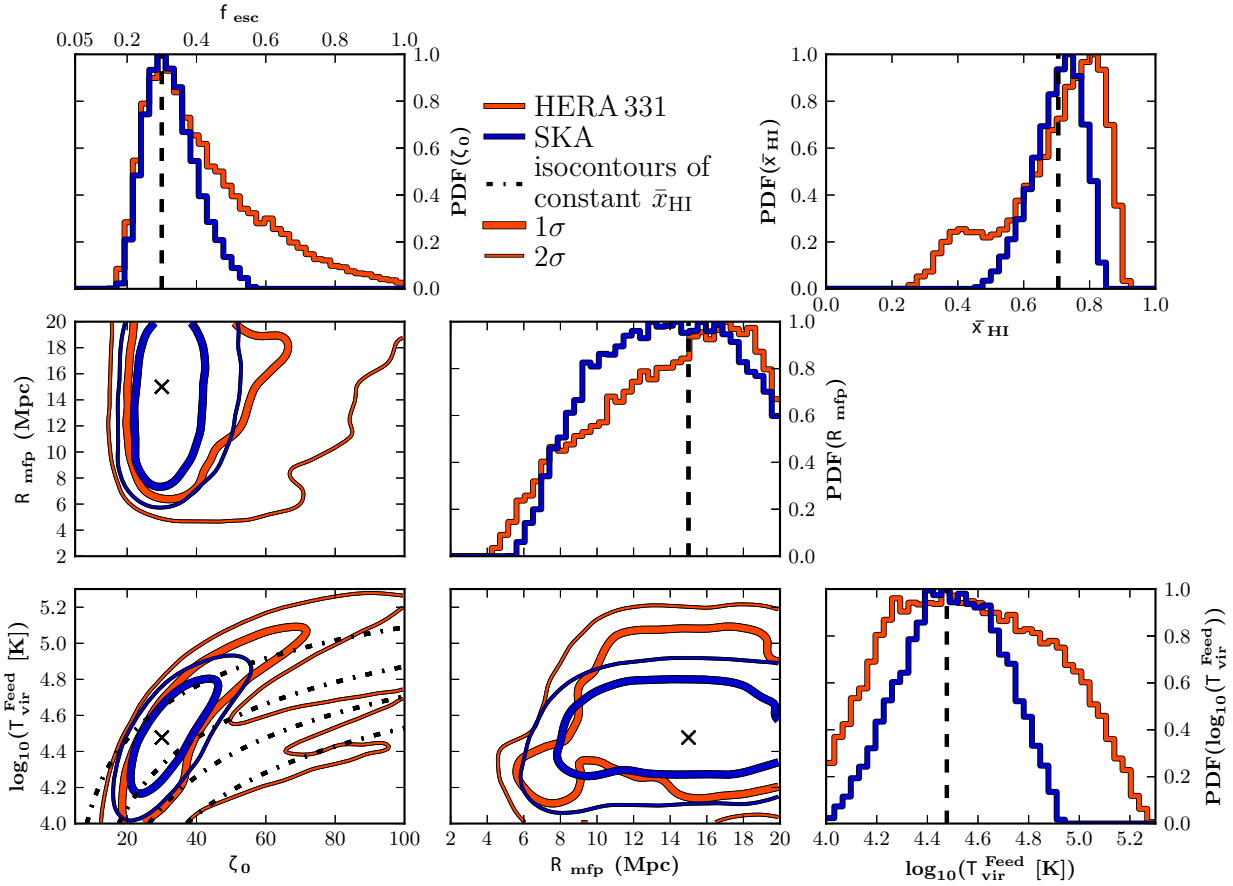



- Limits on $T_{spin}$ can only improve so much
- … and how cold do we expect the IGM to be any way?

Pober *et al.* 2015

# Do We Know What To Do With A Detection?

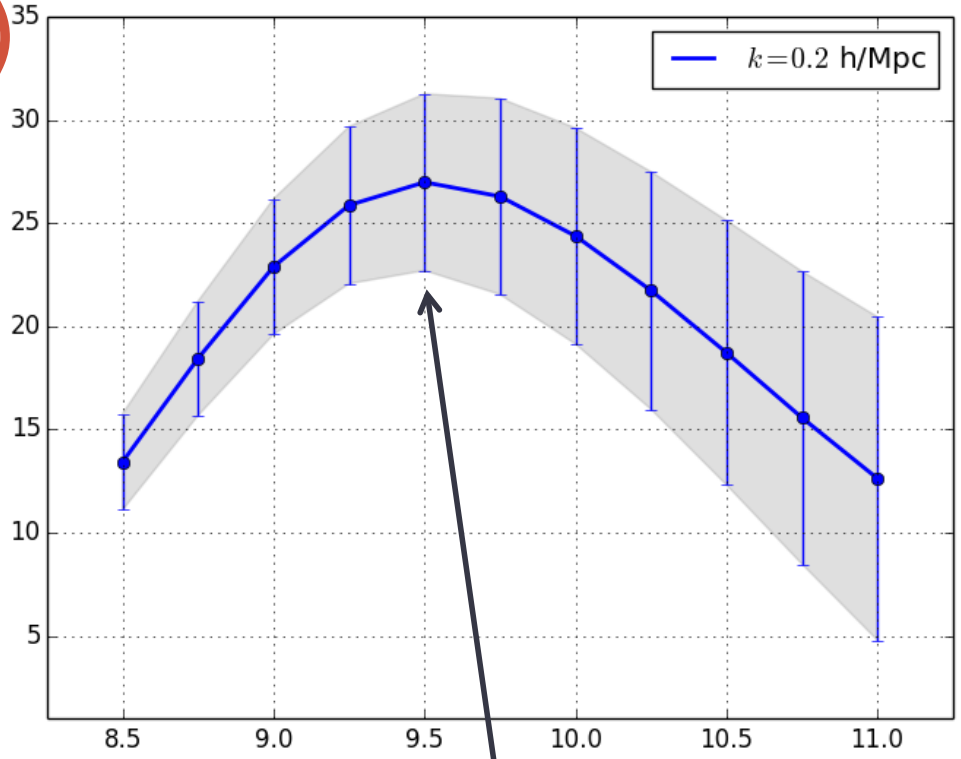
- 21CMMC is a *huge* step forward
- Framework for incorporating other constraints… but what is the common ground?
- How well do ζ, $T_{vir,min}$, & $R_{mfp}$ capture reionization?




Greig & Mesinger 2015

# First detection(s)

- 100 to 200 MHz probes $z \sim 6 - 13$
- Sky noise dominated
  - $T_{sky} \propto (\text{freq.})^{-2.55}$
- Power spectrum noise ($mK^2$) at 200 MHz is up to **35** times larger than at 100 MHz

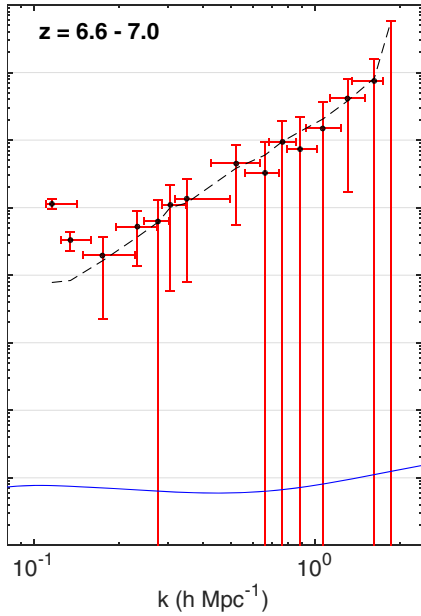



- > 10σ detection at 50% ionization
- No significant detection of peak

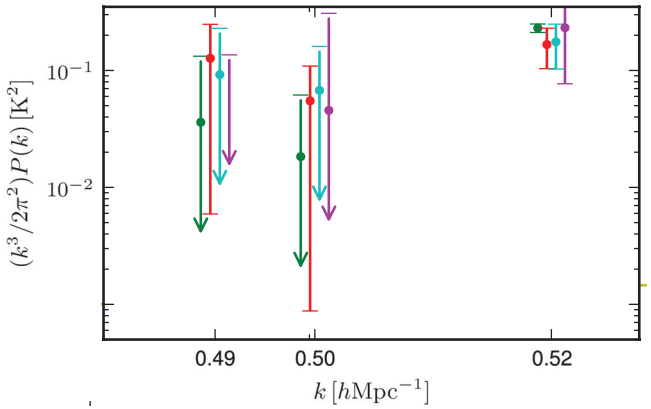
# Would You Believe A Detection?

- Every published 21 cm limit detected *something*

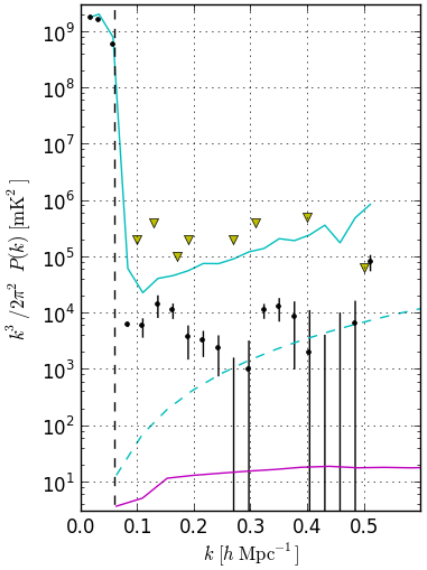
Dillon *et al.* 2015



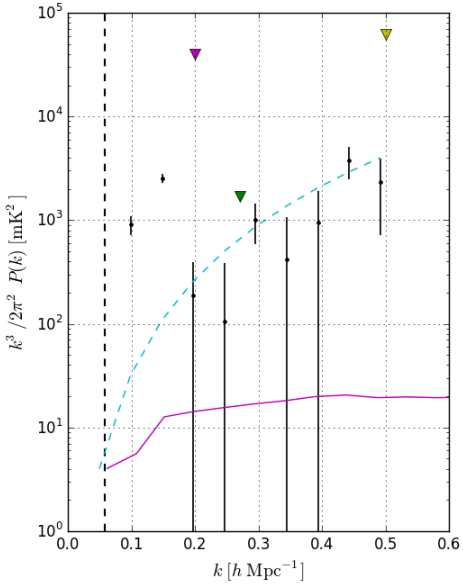

Paciga *et al.* 2014



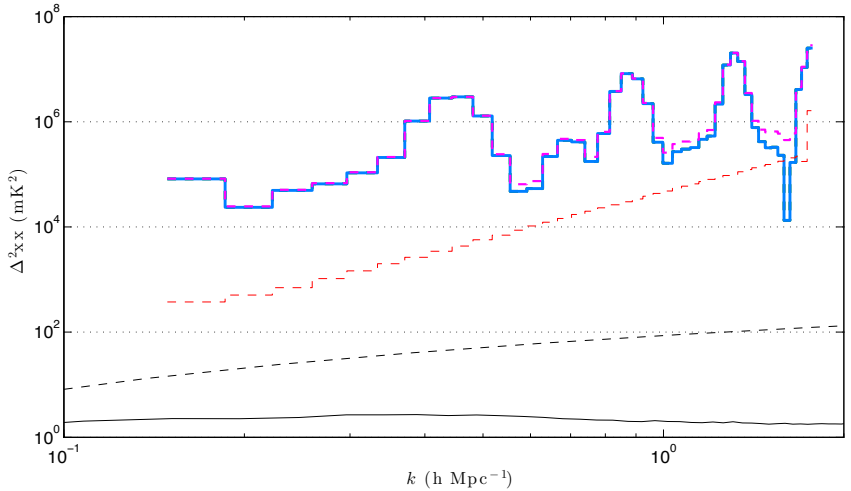

Parsons *et al.* 2014




Ali *et al.* 2015




Beardsley 2015 (thesis)



# Preparing for the 21 cm revolution

- The future for 21 cm studies is bright
  - New techniques
  - Better understanding of systematics
  - Drastic sensitivity increases
  - First framework for recovering physics (21CMMC)
- A detection would be *transformative*
  - What will it take to be conclusive?
- What is the near term science?
  - Is there more to be learned from improved upper limits?
  - What is the science from a first detection?