The Cosmic Twilight Polarimeter (CTP):
A model-independent approach to constrain the synchrotron foreground spectrum for global 21-cm cosmology

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NRAO

NSF

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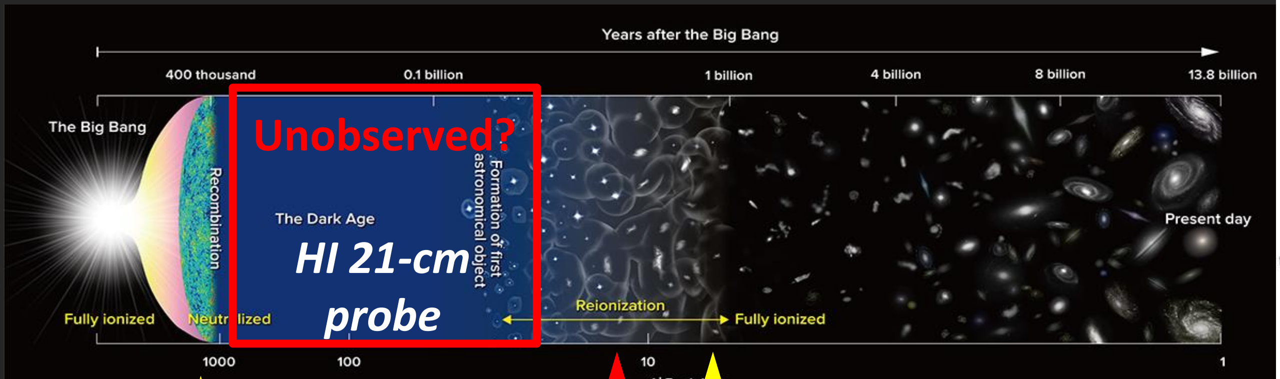
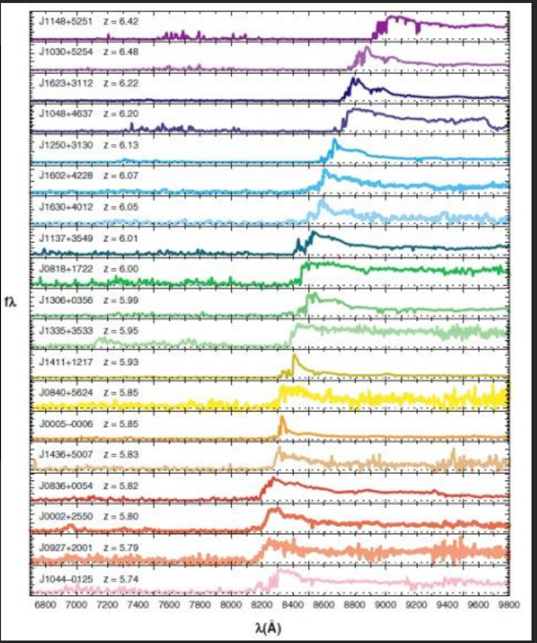
Outline

I. Motivations
II. Projection-induced Polarization Effect (PIPE)
III. The Cosmic Twilight Polarimeter Experiment
IV. CTP Results & Simulation Comparison
V. Discussion & Future Work

High-redshift Universe



Credit: NAOJ



Credit: Fan et al. (2006) *ARAA, 44:415-462*

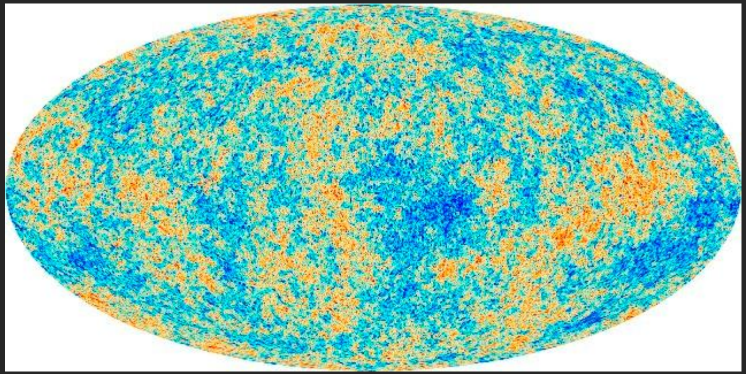
CMB
z ~ 1,100

$\delta T_{CMB}/T_{CMB}$ ~ 10^{-5}

Gunn-Petterson Troughs
EoR ends @ z ~ 6

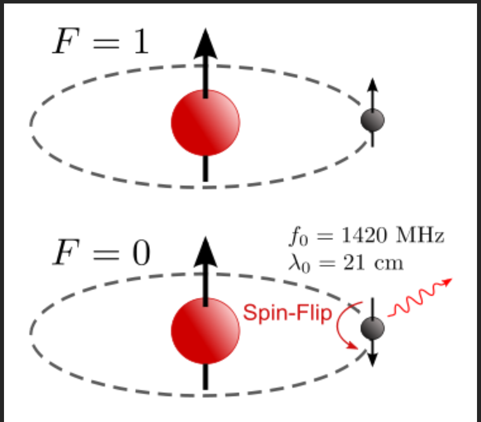
EoR starts @ $z_{re} < 17$

Electron scattering optical depth τ_e



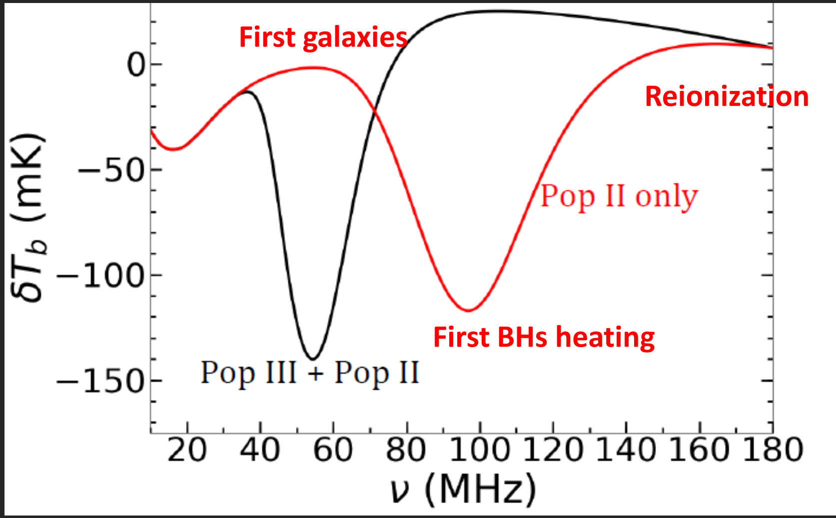
Credit: Planck Collaboration (2016), *AA, 594:A13*

21-cm spin-flip transition of HI atoms



Global = spatially averaged
= sky averaged
i.e., no spatial information

Evolution of global 21-cm signal



Credit: Burns et al. (2018), *ASR 49:433-450*

Ionization history

CMB

Measured against CMB:

$$\delta T_{\rm b,21cm}(z) \approx 27\bar{x}_{\rm HI}\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_\gamma}{T_S}\right)\ {\rm mK},$$

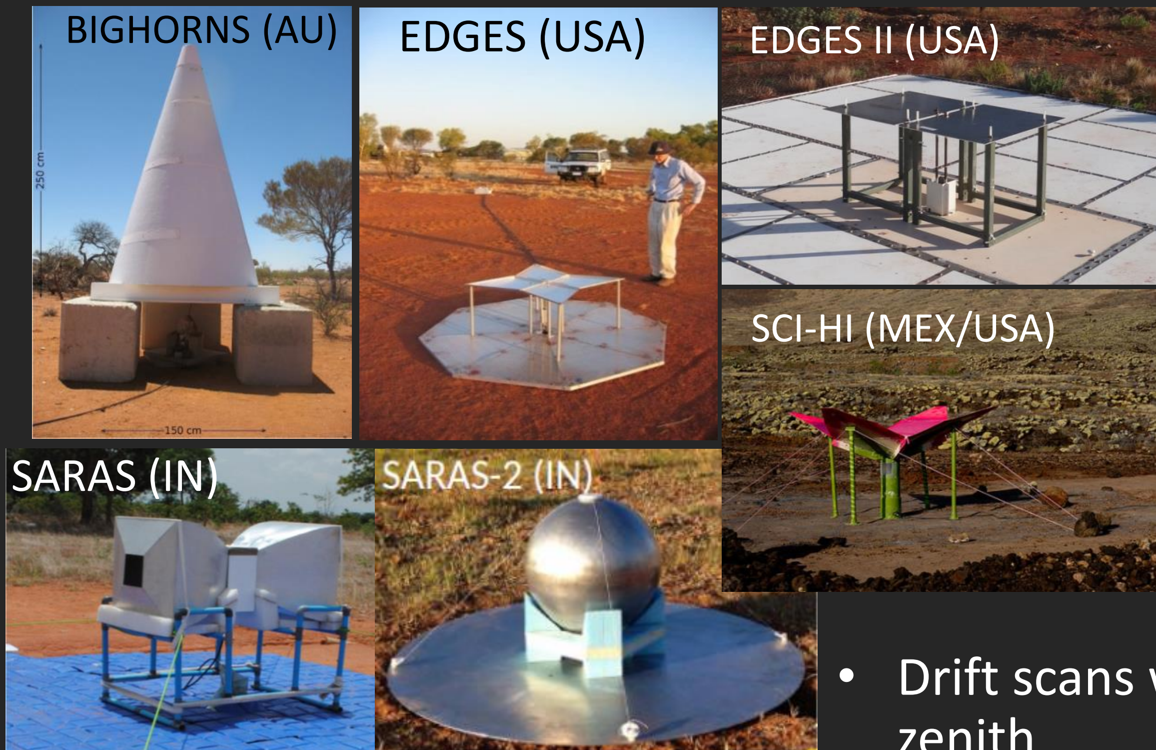
Both function of redshift z

Thermal history

Credit: Furlanetto (2006), *MNRAS, 371:867-878*

Current observational efforts

Single element



Lower cost than large arrays

Compact Array

- Drift scans with antennas pointing at zenith
- Total-power measurement: (Foreground + 21 cm) in a *single averaged spectrum*

→ Environment, measurement & systematic variations

Why is it a tricky measurement?

Beam weighted measurement

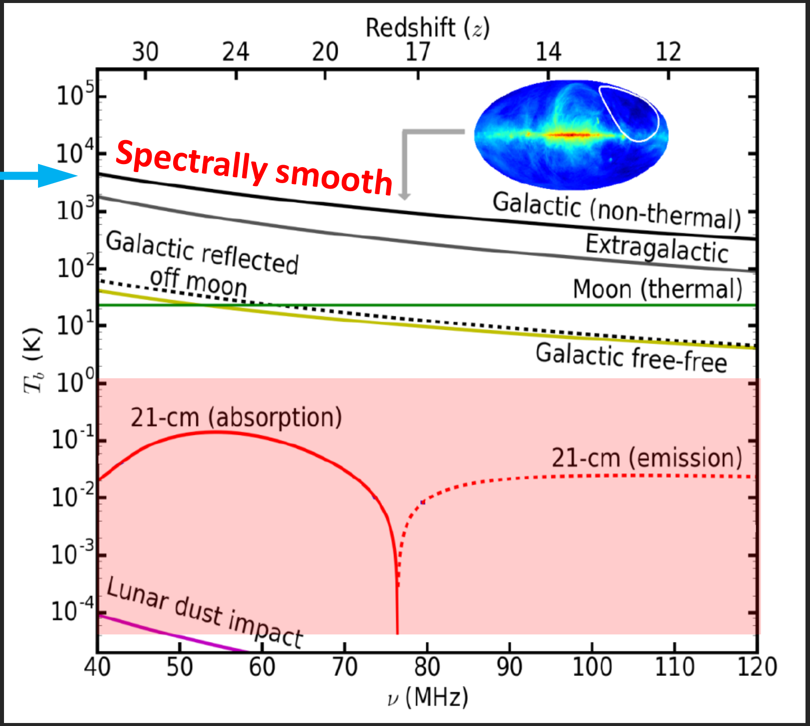
$$T_{\rm ant}(\nu) = \frac{\int_{\Omega_B} [T_{\rm fg}(\nu,\theta,\phi) + \delta T_{\rm b,21cm}(\nu,\theta,\phi)]\, F(\nu,\theta,\phi)\, {\rm d}\Omega}{\int_{\Omega_B} F(\nu,\theta,\phi)\, {\rm d}\Omega}$$

$$= T_{\rm fg}(\nu) + \delta T_{\rm b,21cm}(\nu)$$

Antenna Temperature
(Foreground+ 21 cm)

Foreground parametrization:

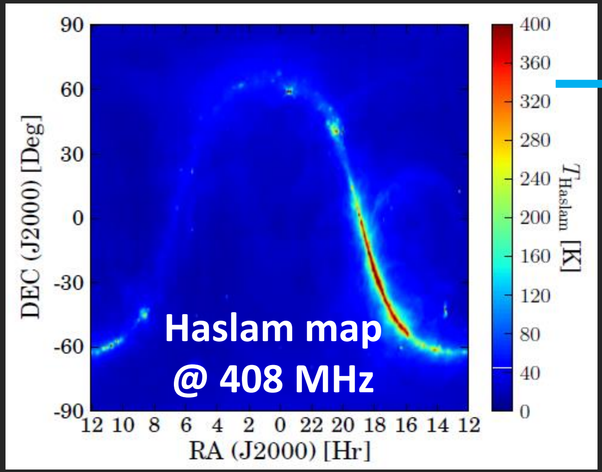
$$\log \widehat{T}_{\rm fg}(\nu) = \sum_{m=0}^{M>0} c_m (\log \nu)^m$$



1. Large dynamic range (4-6 orders of magnitude)
2. Beam is a complex function of frequency

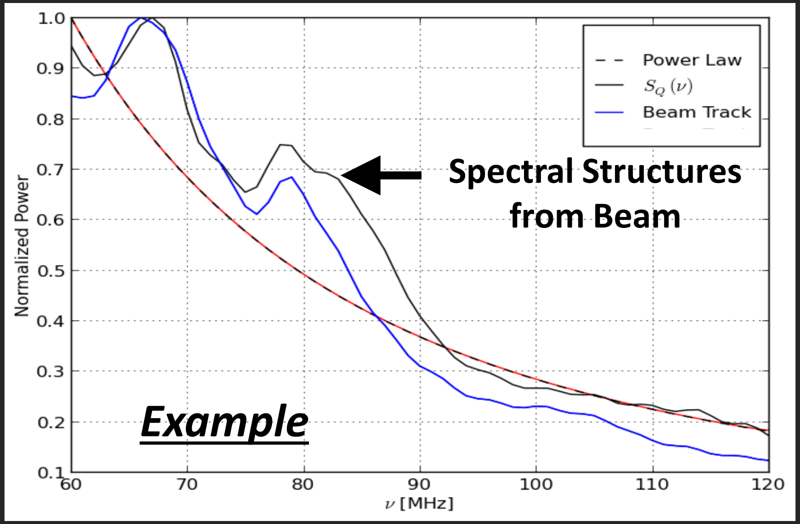
Credit: Burns et al. (2017), *ApJ, 844:33*

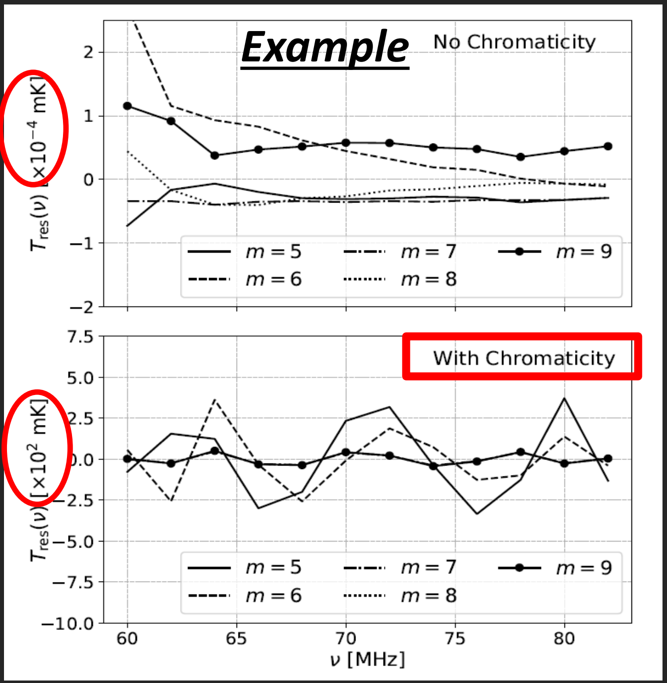
Conventional Foreground Removal



Spectrally smooth foreground :

$$T_{fg}(\theta,\phi,\nu) = T_{\text{Haslam}}(\theta,\phi)\left(\frac{\nu}{408\ \text{MHz}}\right)^{-\beta}$$

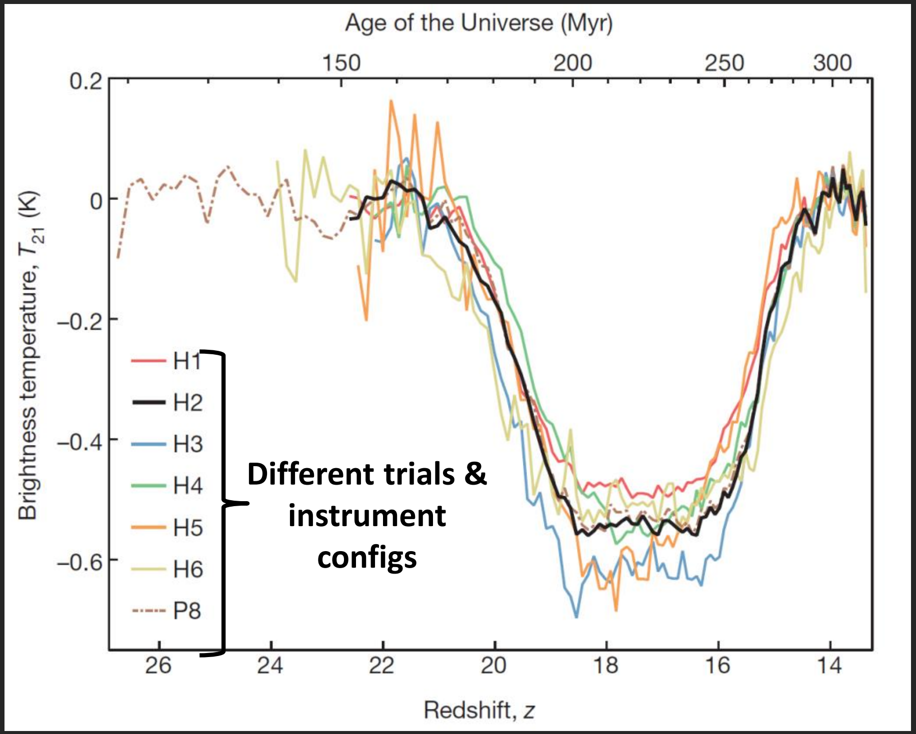




$$\log \widehat{T}_{\text{fg}}(\nu) = \sum_{m=0}^{M>0} c_m (\log \nu)^m$$

Beam corrupts foreground smoothness
→ Large residual

Recent measurement (March 2018)



Credit: Bowman et al. (2018) *Nature, 555:67*

- EDGES-II (low-band 50-100 MHz):
  Trough @ 78 ± 1 MHz
  Amplitude ≈ $0.5^{+0.5}_{-0.2}$ K
  FWHM ≈ 19^{+4}_{-2} MHz

Sophisticated foreground parametrization:

$$T_{\mathrm{F}}(\nu) = b_0 \left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5+b_1+b_2\log(\nu/\nu_{\mathrm{c}})} \mathrm{e}^{-b_3(\nu/\nu_{\mathrm{c}})^{-2}} + b_4 \left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2}$$

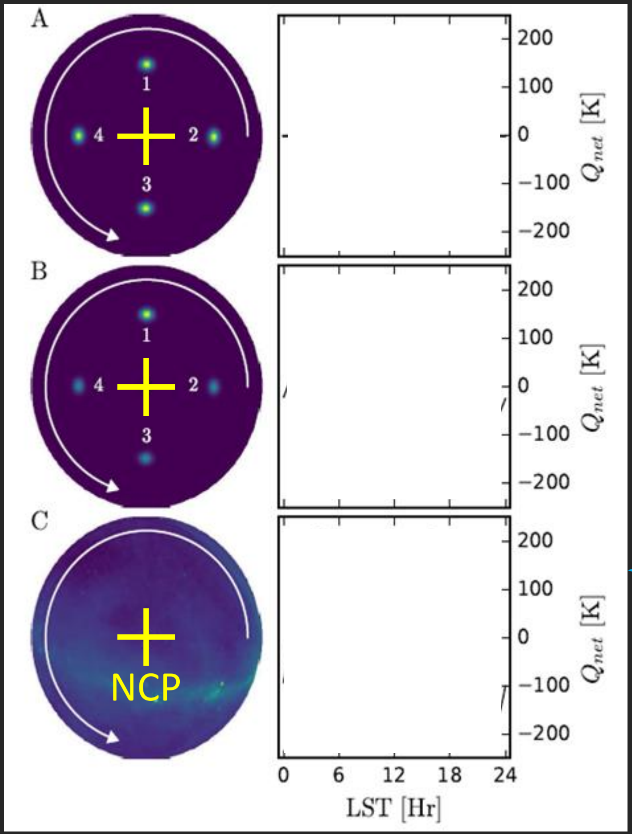
Ionosphere absorption | **Ionosphere refraction**

→ Need independent confirmation from separate experiment & different approach and systematics

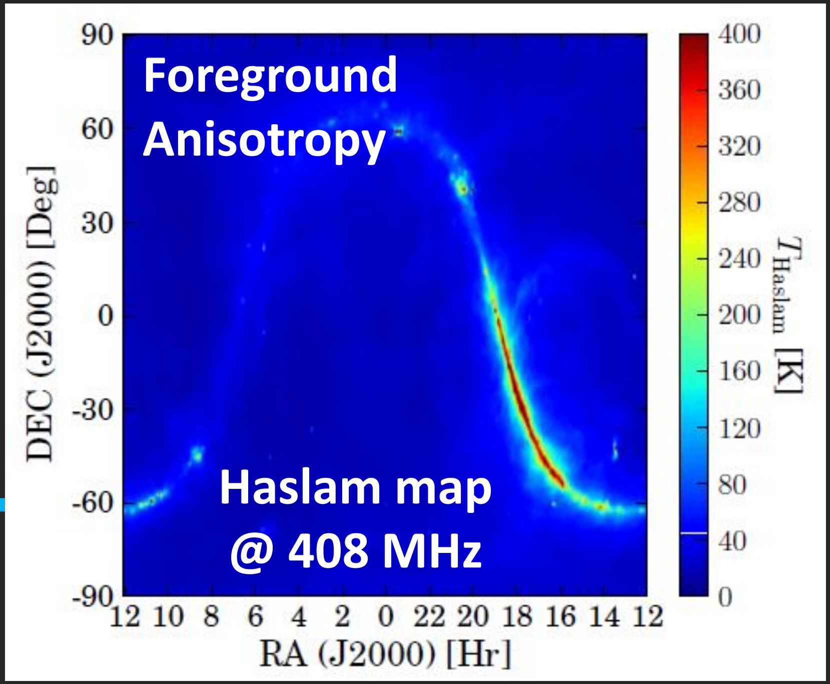
What do we want?

- Measure foreground spectrum **directly** without assuming any parametrization for fitting
- Measure foreground **separately** without being “convoluted” with the background 21-cm signal as in a single total-power spectrum

Projection-induced polarization effect (PIPE)



Cross dipole



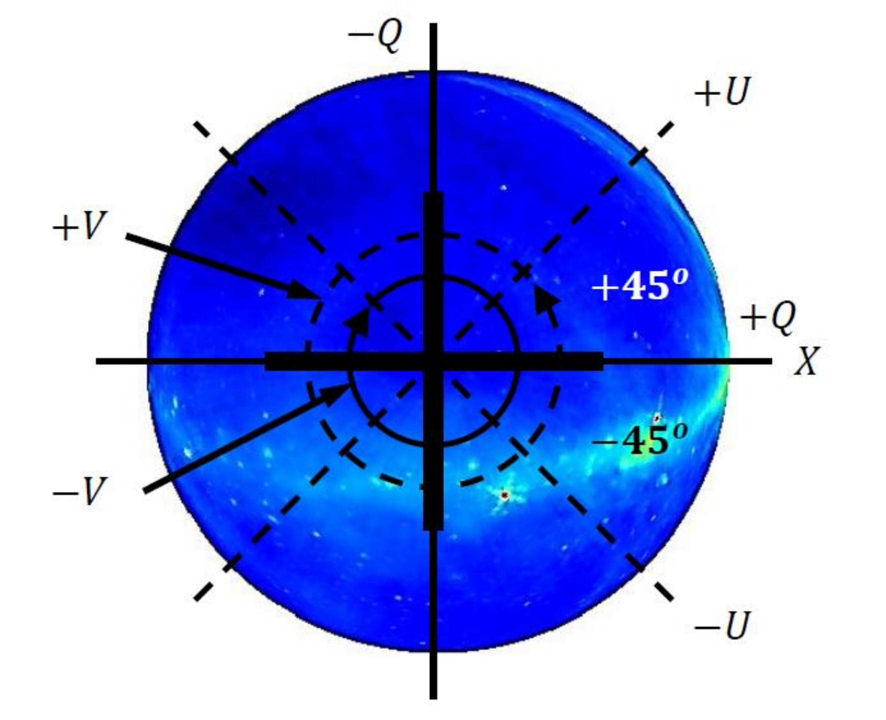
Credit: Haslam, et al. (1982), *NASA archive data*

→ Asymmetry foreground induced periodic net polarization

→ Isotropic global background = zero net polarization

→ Geometric effect, NOT intrinsic foreground polarization (much weaker & washed out by spatially averaging)

Stokes formalism



Total Stokes parameters:

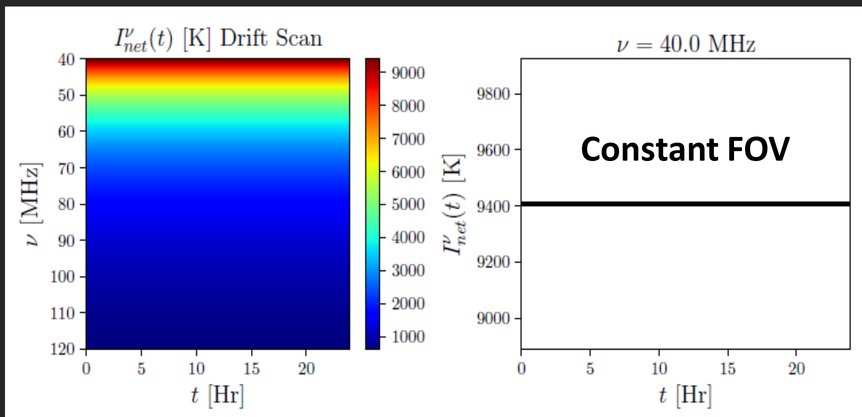
$$
\begin{aligned}
I^{\nu}_{out}(\theta,\phi,t) &= \langle E_X E_X^* \rangle + \langle E_Y E_Y^* \rangle \\
Q^{\nu}_{out}(\theta,\phi,t) &= \langle E_X E_X^* \rangle - \langle E_Y E_Y^* \rangle \\
U^{\nu}_{out}(\theta,\phi,t) &= \langle E_X E_Y^* \rangle + \langle E_X^* E_Y \rangle \\
V^{\nu}_{out}(\theta,\phi,t) &= j\left(\langle E_X E_Y^* \rangle - \langle E_X^* E_Y \rangle\right)
\end{aligned}
$$

→ Net Stokes vector measures
the projection-induced polarization
Foreground ONLY

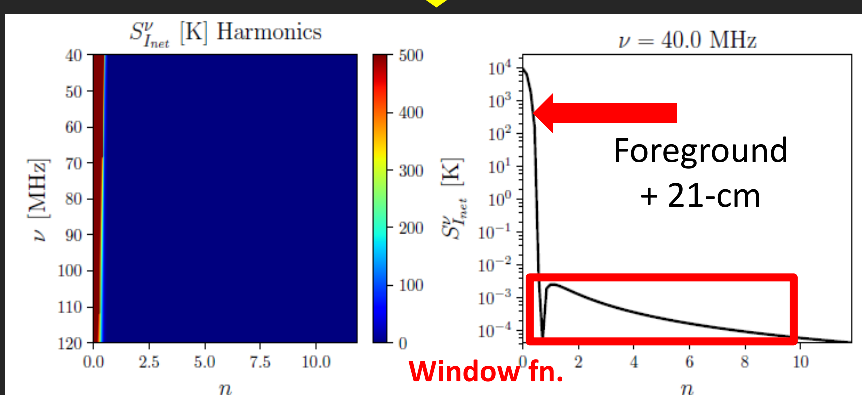
Simulation:

$$T_{fg}(\nu) = T_{150}\left(\frac{\nu}{150\ \mathrm{MHz}}\right)^{-\alpha}$$

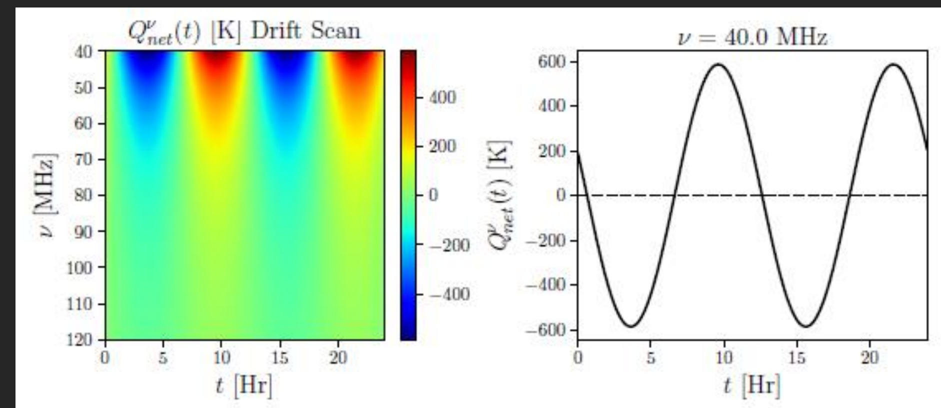
Total Stokes I



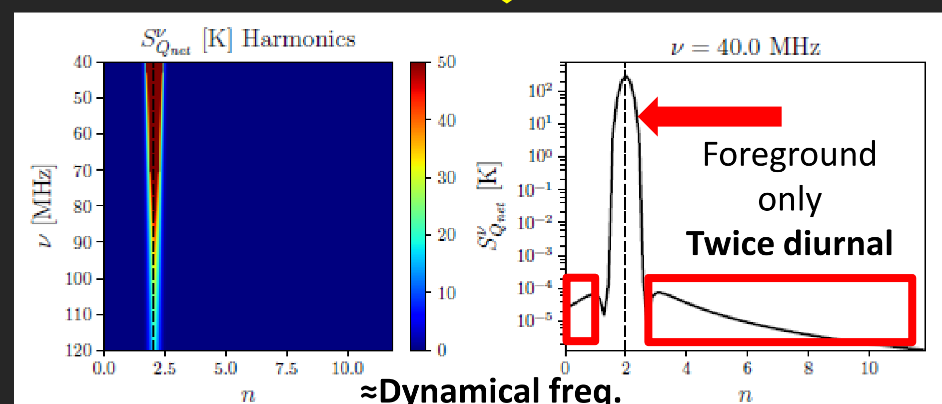
FFT



Net Stokes Q



FFT

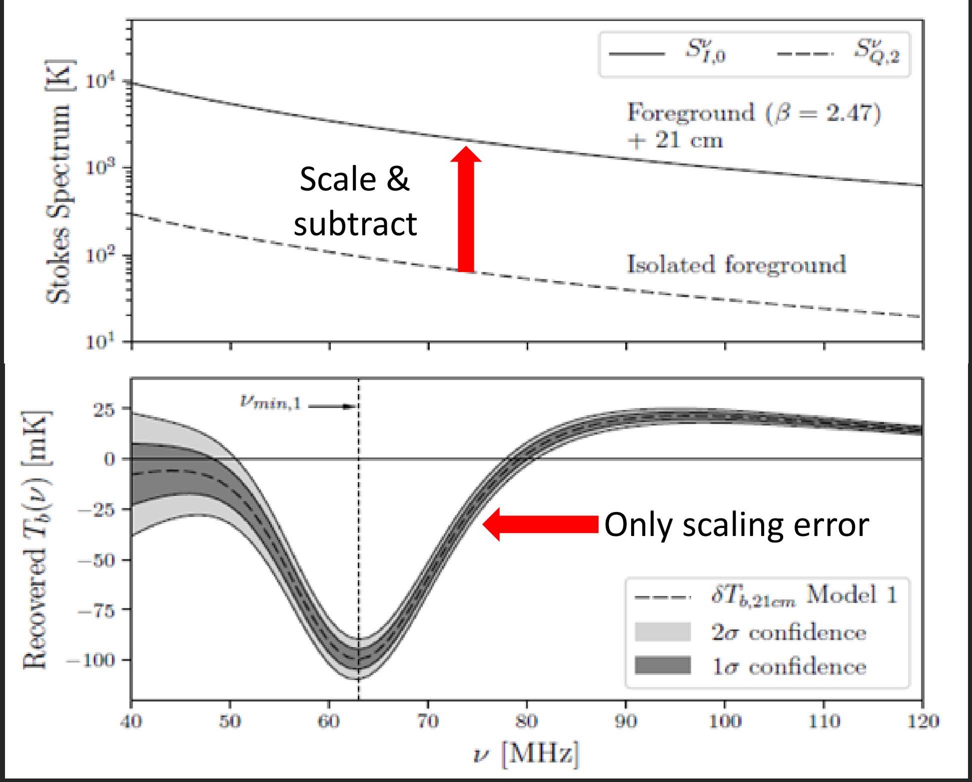


Credit: Nhan et al. (2017) *ApJ , 836:90*

Foreground subtraction with induced Stokes spectra

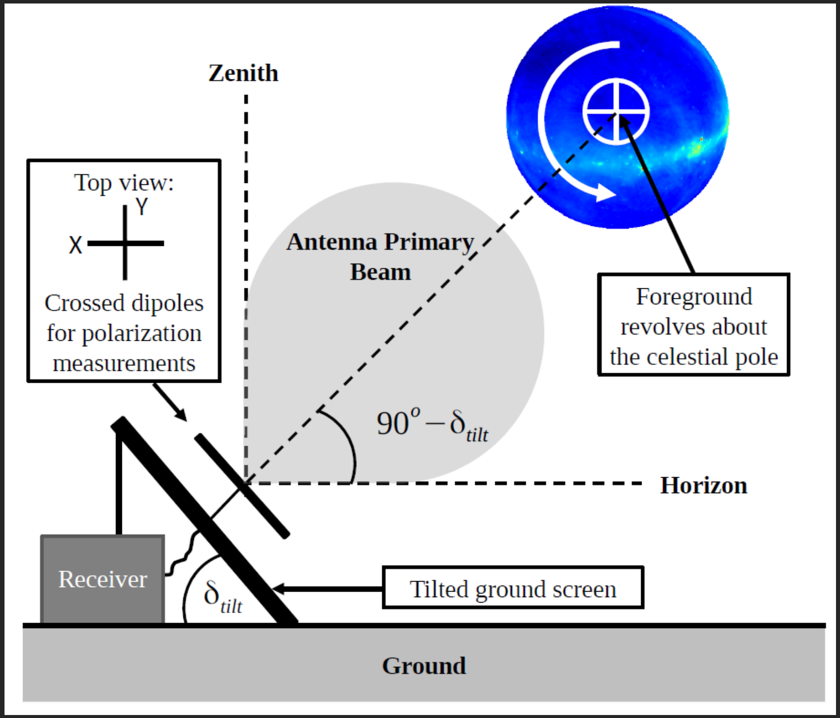
<u>Caveats</u>:

- Gaussian beam
- Frequency-independent beam
- Observed at North Pole
  → Free from horizon cutoff of northern sky



<u>*Credit*</u>: Nhan et al. (2017) *ApJ , 836:90*

Cosmic Twilight Polarimeter (CTP)

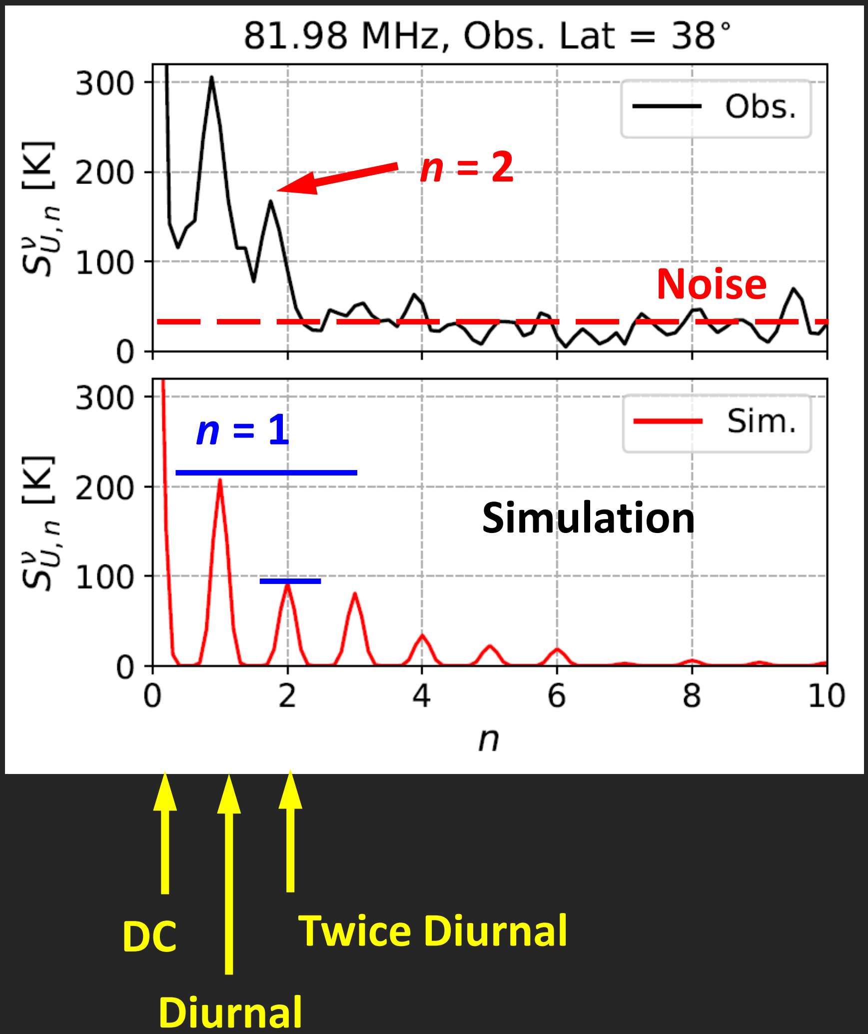


Credit: Nhan et al. (2017) *ApJ , 836:90*

What's new vs other experiments?

- Full Stokes, not just total power
- Point antenna at North Celestial Pole (NCP)

Stokes *U* Spectra (from FFT)



1) S/N for (*n=2*) = 4.23

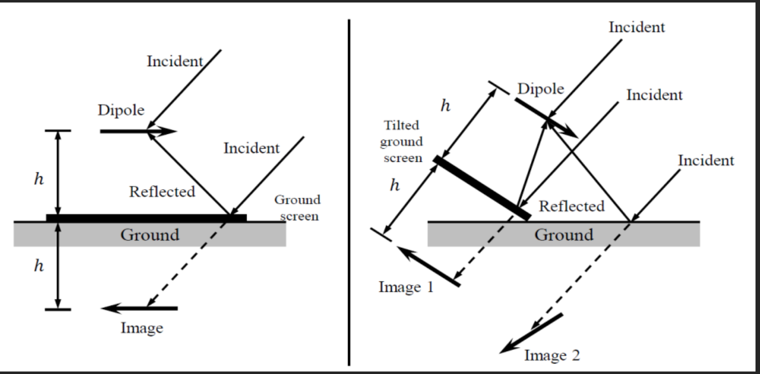
2) Relative harmonic ratio:
- Sim(n=1:2) = 2.24
- Obs(n=1:2) = 1.83 ± 0.5

Marginal detection of the twice diurnal

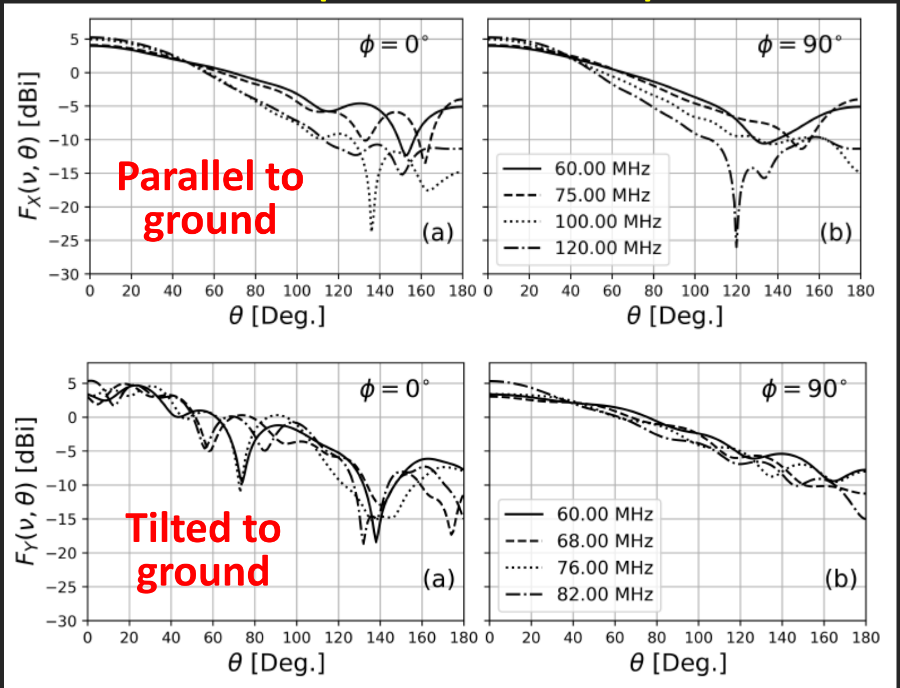
- **Don't have entire band to confirm the spectral index of the foreground**

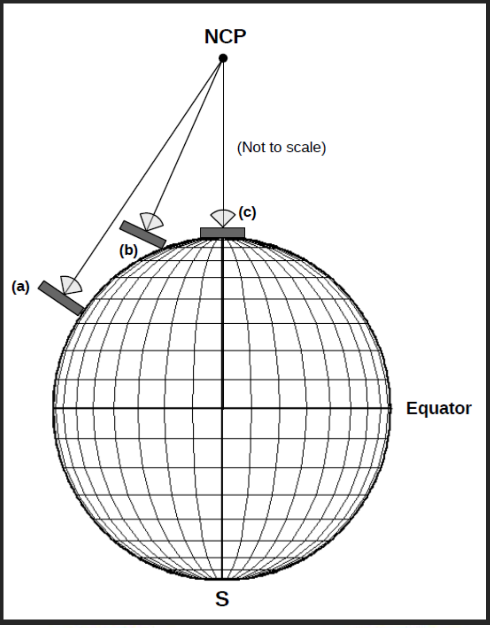
Ground effects

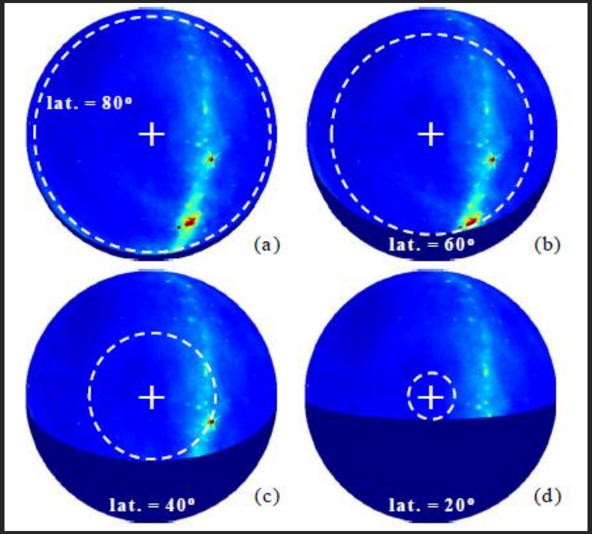
Horizon Obstruction



Beam simulation using CST (EM sim software)

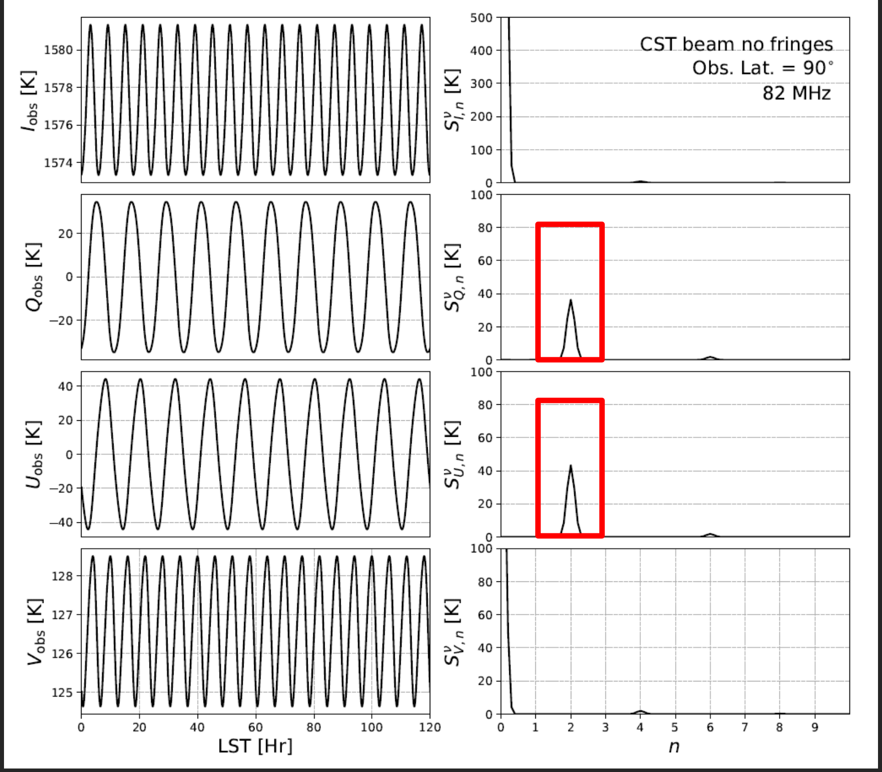


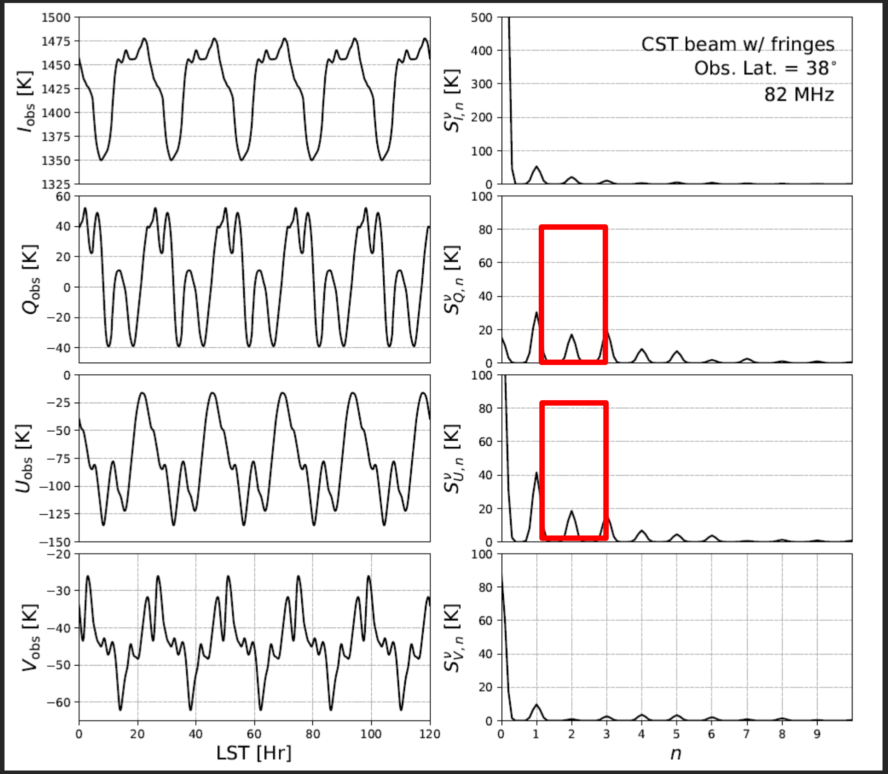




Idealized Model

Model (CST tilted beam + horizon)





Model with ground effect on beam & horizon cutoff explains the observed characteristics in the CTP's Stokes spectra

Takeaways

- New approach to constrain foreground using projection induced polarization
  - **1) Move the antenna high off the ground to reduce the corruption**
  - **2) Move the experiment to higher latitude to reduce horizon obstruction**
- Full Stokes provides higher degree of freedom to constrain foreground **directly** & **separately** from background 21-cm signal (vs. total-power)
- Great potential to do a follow up observation for the global 21-cm signal to confirm EDGES's result

THANK YOU!

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