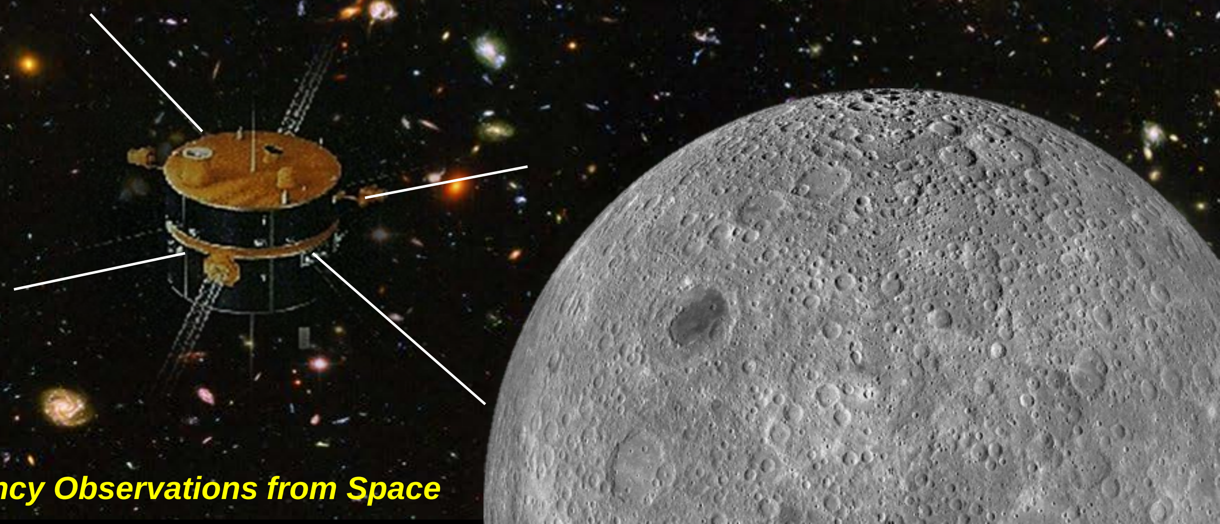
Network for Exploration and Space Science
A NASA-funded SSERVI Team

A Space-Based Observational Strategy for Hydrogen Cosmology Using Dynamic Polarimetry and Pattern Recognition

Jack Burns[1], Bang Nhan[1,2], Rich Bradley[2], Keith Tauscher[1], David Rapetti[1,3], Eric Switzer[4]
[1]University of Colorado Boulder, [2]NRAO, [3]NASA ARC, [4]NASA GSFC



AAS Meeting-in-a-Meeting: ***Low Radio Frequency Observations from Space***

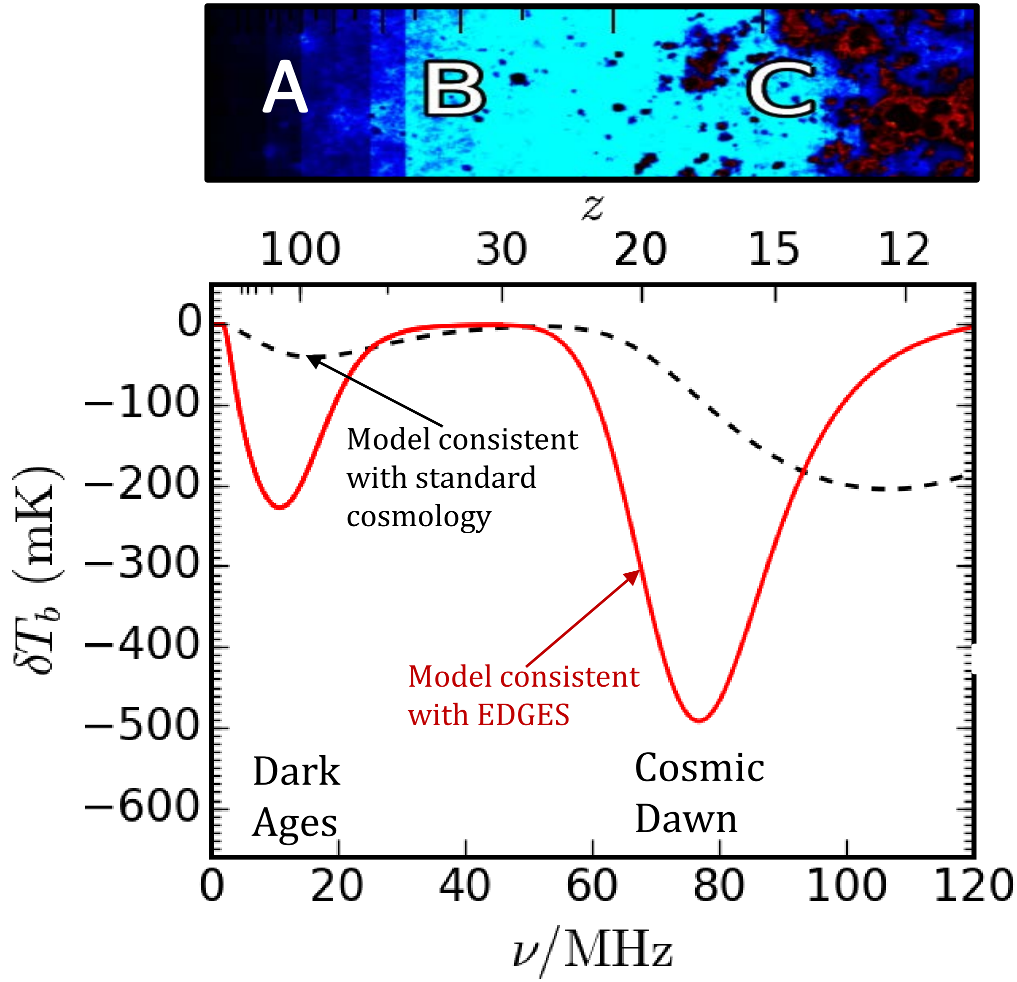
What is the 21-cm Global signal?

Spectral Features:

A: Dark Ages (test of standard cosmological model)

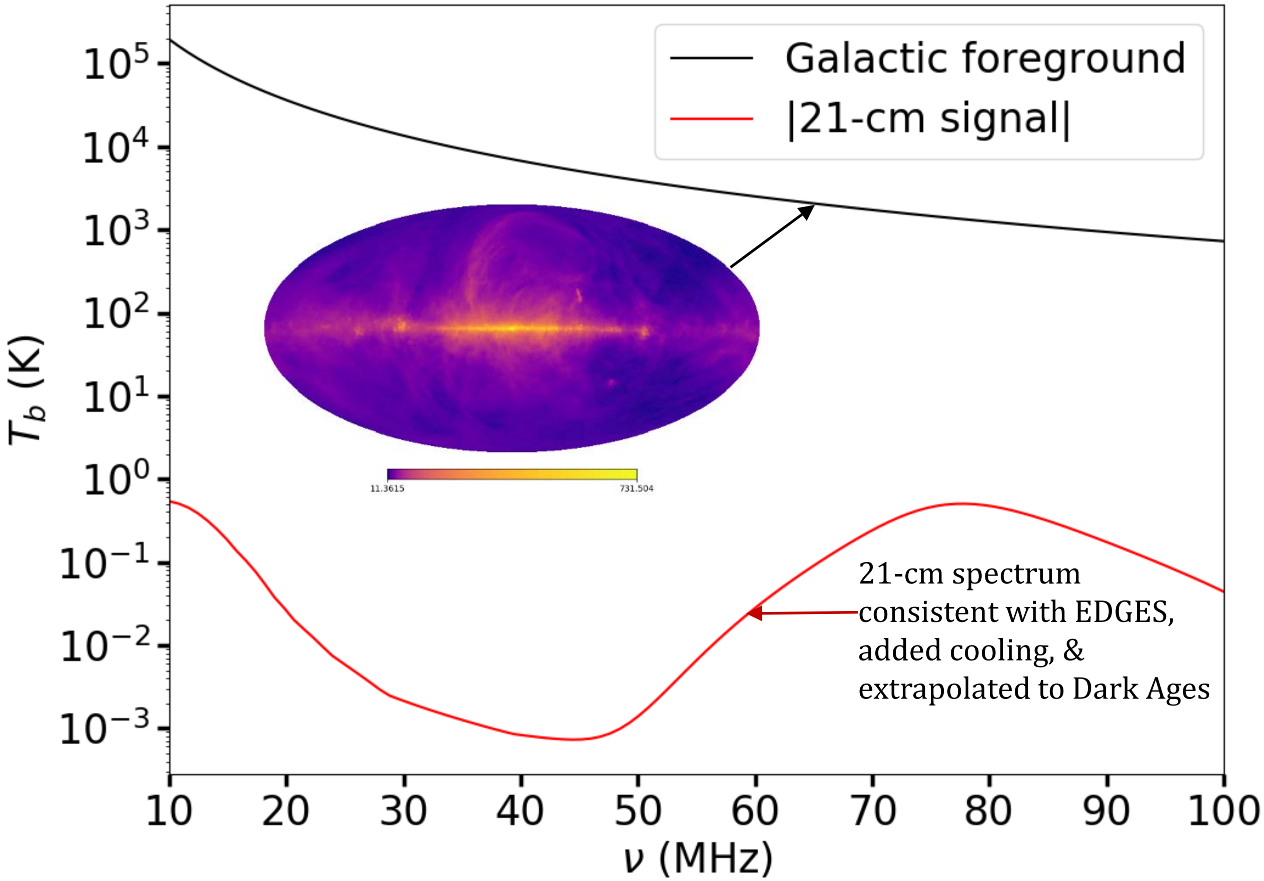
B: First stars ignite (Cosmic Dawn)

C: Black hole accretion begins



Models courtesy of Jordan Mirocha

Why is this a Challenging Observation?



Foreground Characteristics

- Spectrally smooth
- Spatial structure
- Polarized

Signal Characteristics

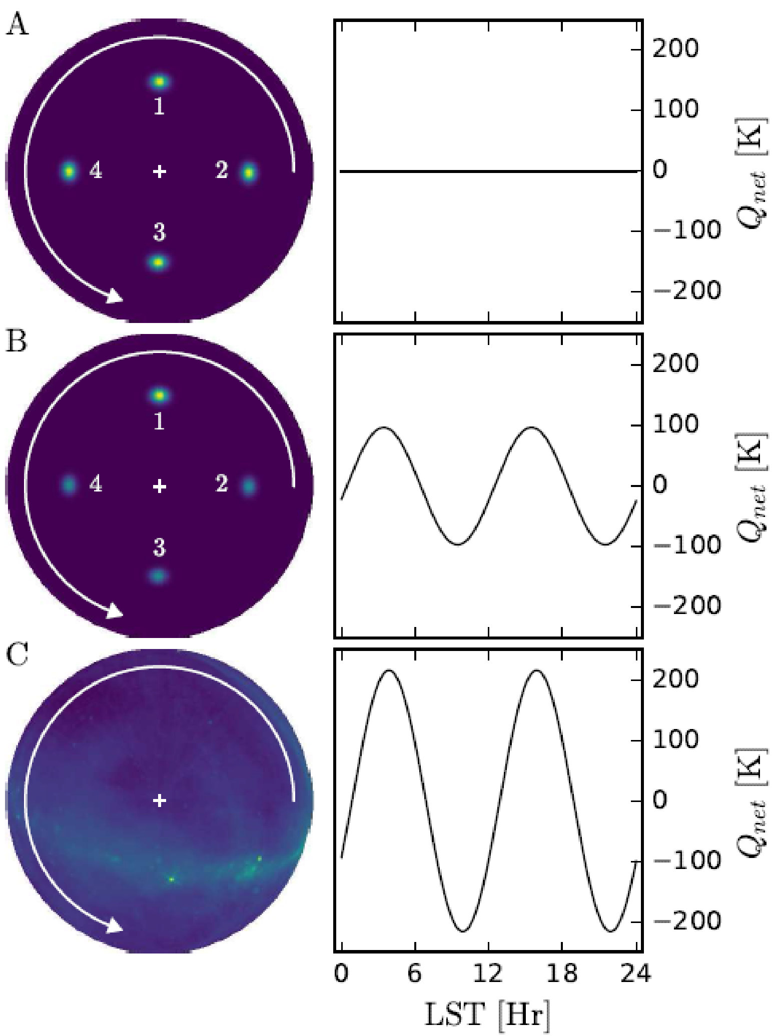
- Spectral structure
- Spatially isotropic
- Unpolarized

$$T_{ant}(\nu) = \frac{\int_0^{2\pi}\int_0^{\pi/2} T_{sky}(\nu,\theta,\phi)F(\theta,\phi,\nu)\sin\theta \mathrm{d}\theta\mathrm{d}\phi}{\int_0^{2\pi}\int_0^{\pi/2} F(\theta,\phi,\nu)\sin\theta \mathrm{d}\theta\mathrm{d}\phi}$$

Weighting by antenna beam introduces spectral structure in foreground (e.g., Bernardi *et al.* 2015, Mozdzen *et al.* 2016)

How Can Polarimetry Help?

Projection-Induced Polarization (Nhan, Bradley, Burns, 2017, ApJ, 836, 90)



Ideal Simulation of the Dynamic & Asymmetric Foreground

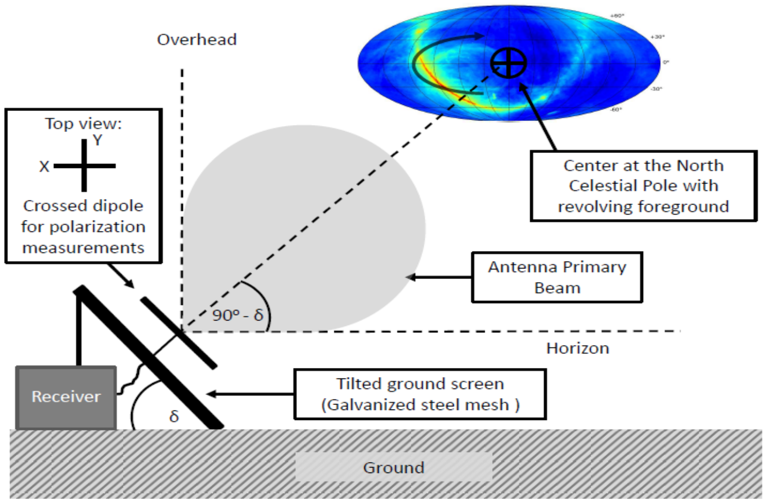
A. *4 symmetric point sources* revolving about pointing center

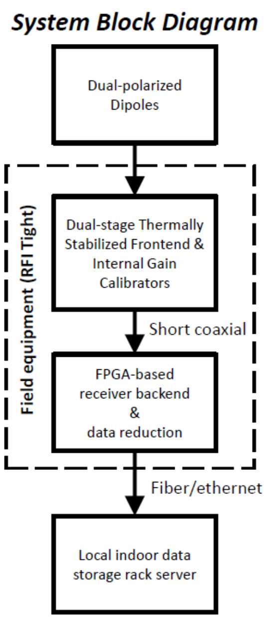
B. *3 weak sources & 1 strong source* revolving

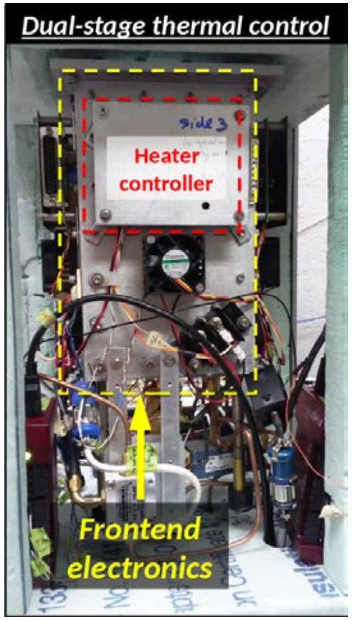
C. *Actual sky map* (Haslam et al. 1982) centered on North Celestial Pole

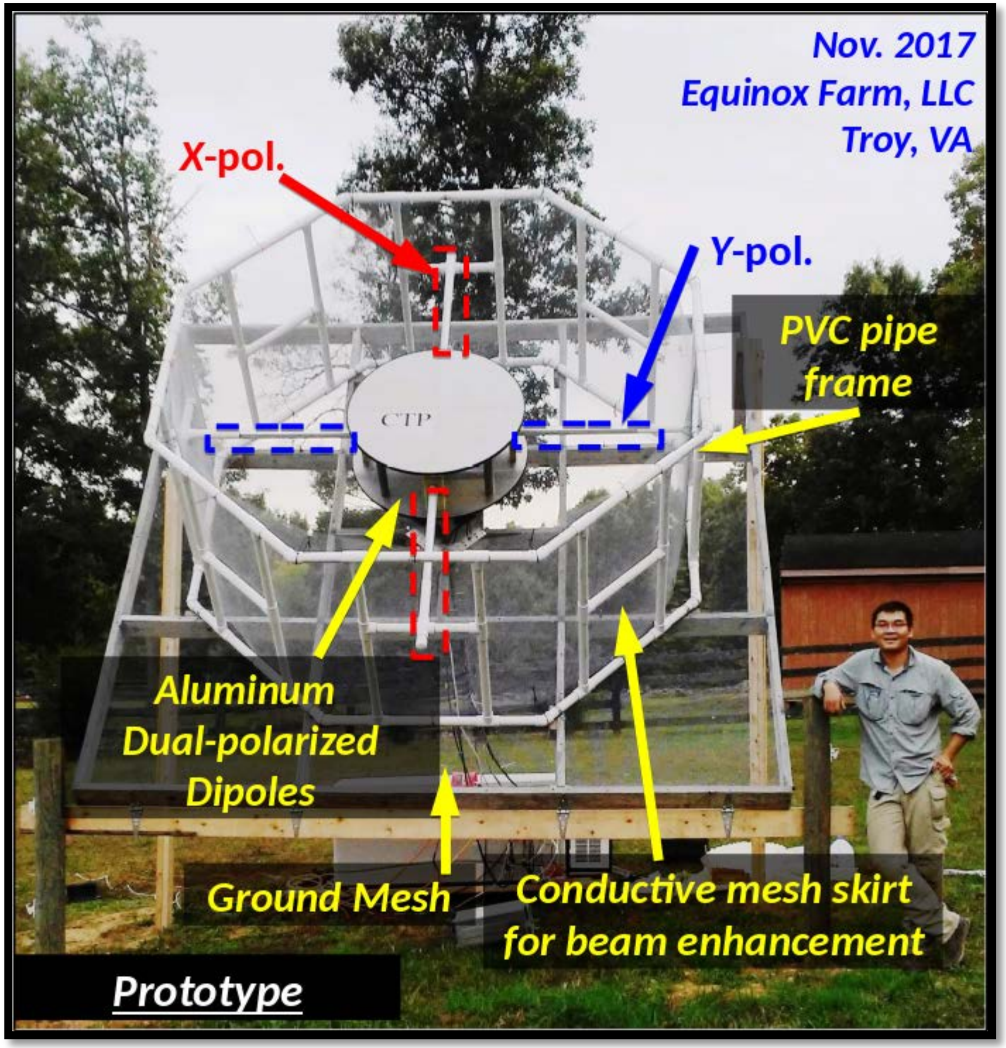
Remember: No net polarization expected from isotropic global 21-cm signal

The Cosmic Twilight Polarimeter (CTP): Dynamic Polarimetry Testbed







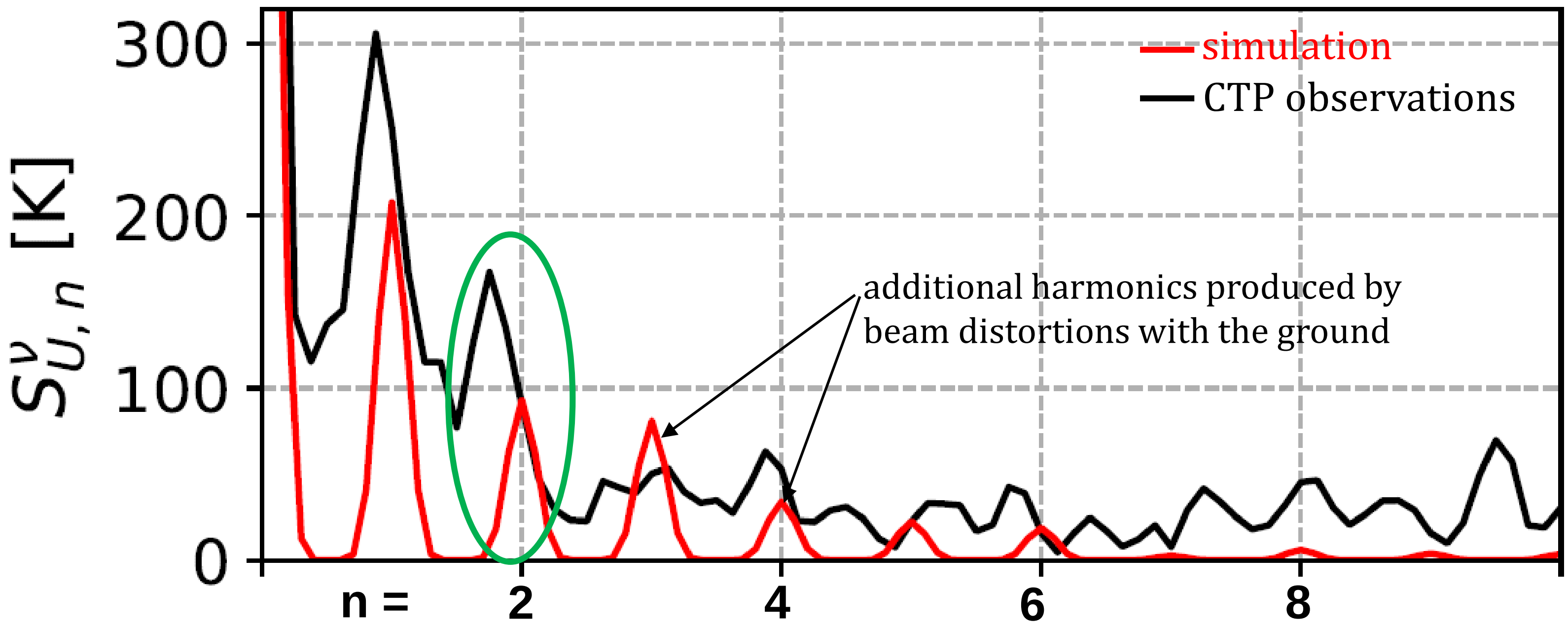


Operates over 60-80 MHz

Nhan, Bradley, & Burns, 2018

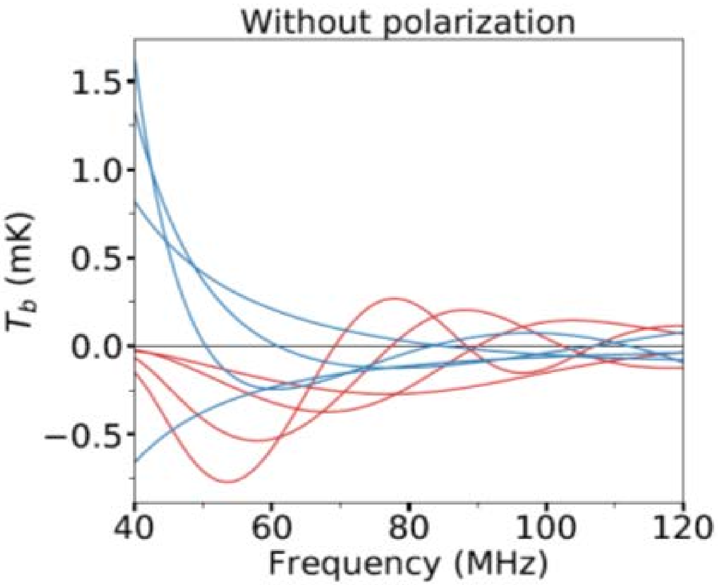
Initial Results from the Cosmic Twilight Polarimeter

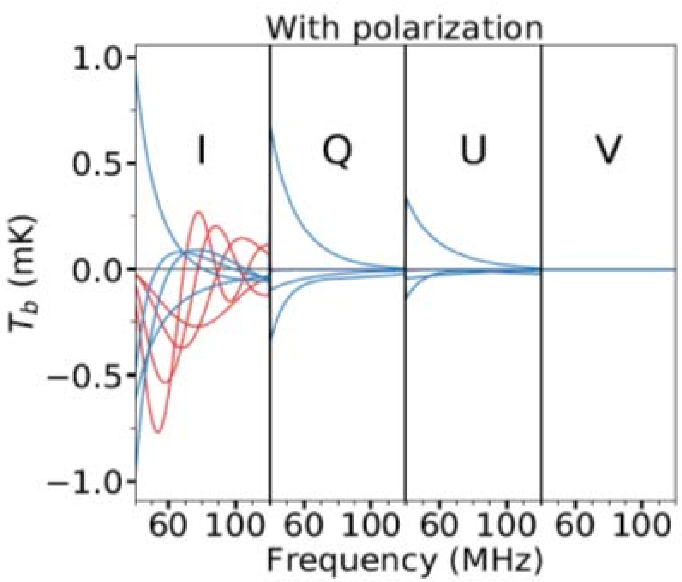
Nhan, B., 2018, Ph.D. dissertation, U. Colorado



- Data consist of Stokes I,Q,U,V in frequency channels as a function of time at ≈82 MHz.
- After extensive RFI editing and averaging, Fourier transform binned data channels to measure dynamical frequencies (n) for Stokes Q,U.
- n = 2 is expected twice diurnal signal and is tentatively detected in these data.
- Caveats:
  - Simulation only contains first order models of beam distortions due to ground and horizon effects.
  - Very few clean channels due to severe RFI.

How can we extract the 21-cm signal?





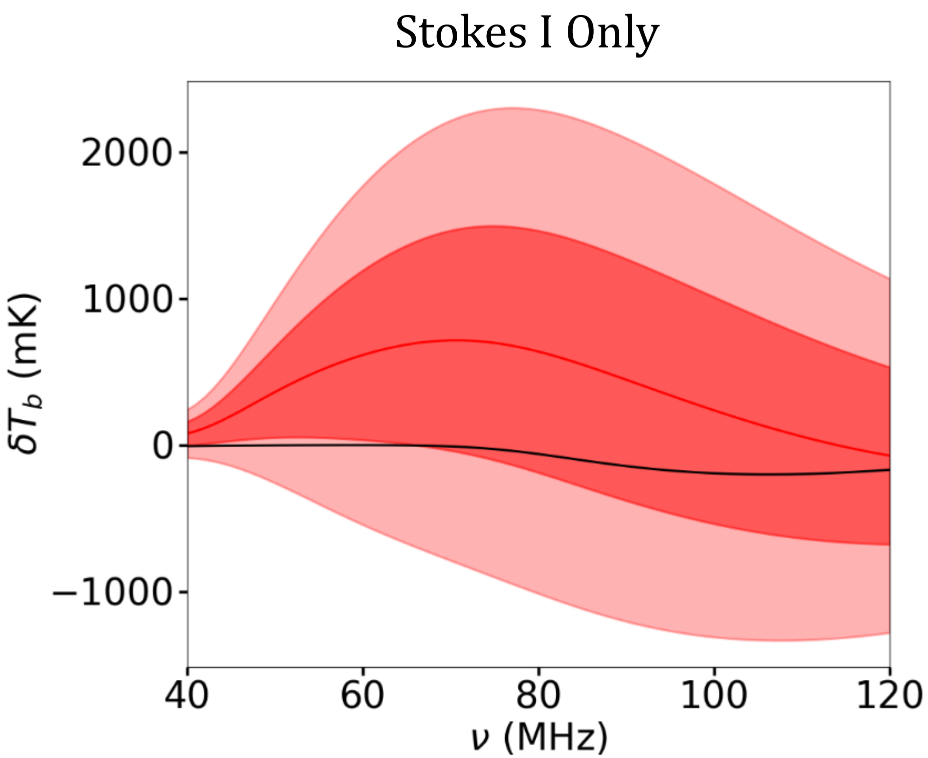
Employ Pattern Recognition Techniques:

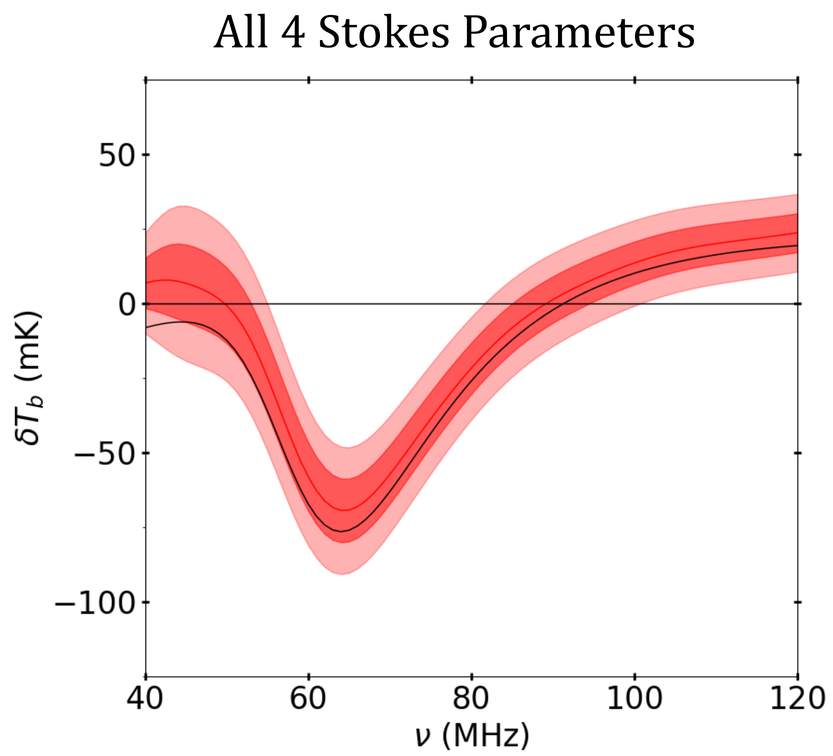
- Extract basis vectors from training sets using **Singular Value Decomposition (SVD)**
- SVD is a machine learning tool equivalent to:
  - Principal Component Analysis (PCA)
  - EigenVector Decomposition (EVD)

See also at the meeting:

- Next talk by D. Rapetti, 312.03, ***SVD/MCMC Pipeline for Separating the Global 21-cm Signal from Foregrounds/ Systematics.***
- Poster by K. Tauscher, 319.05, ***Characterizing the 21-cm absorption trough with pattern recognition and a numerical sampler.***

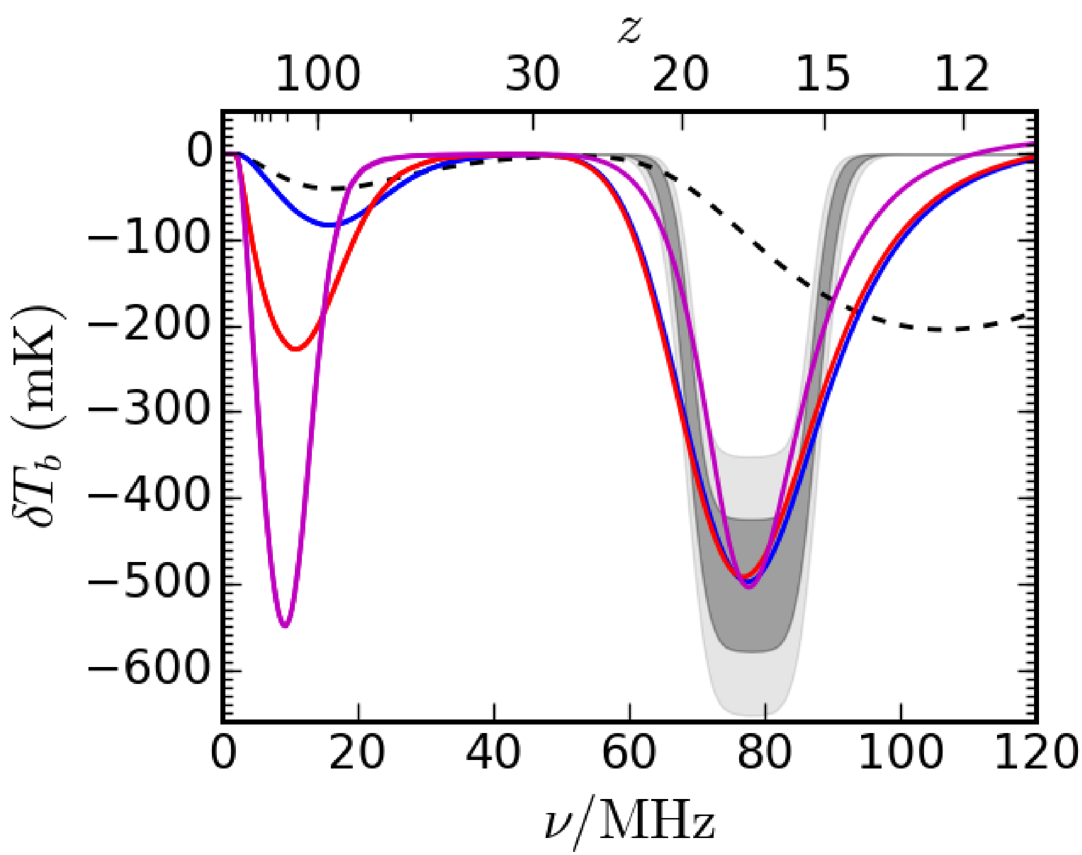
How much difference does polarization data make?





- **Burns et al. 2017,** *A Space-based Observational Strategy for Characterizing the First Stars and Galaxies Using the Redshifted 21cm Global Spectrum*, ApJ, 844, 33.
- **Tauscher, K., Rapetti, D., Burns, J., Switzer, E.** 2018, *Global 21-cm Signal Extraction from Foreground & Instrumental Effects I: Pattern Recognition Framework for Separation Using Training Sets,* ApJ, 853, 187 (1 Feb. 2018).

Extrapolation into the Dark Ages based upon EDGES Results



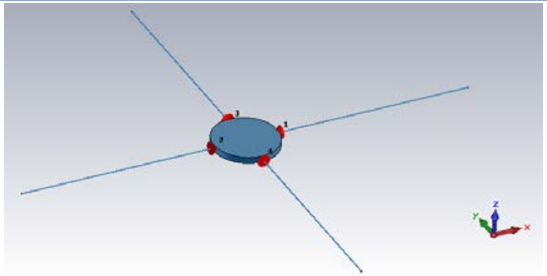
- **68 and 95% (dark and light gray) bands:** EDGES measurements of **Cosmic Dawn.**
- **Black, dashed curve:** Example of the **standard** astrophysical models ***inconsistent with EDGES results***.
- EDGES results (Bowman et al. 2018, Nature, 555, 67) *require exotic physics* such as e.g. interactions between baryons and dark matter particles.
- *Beyond-standard-physics* models of the **Dark Ages** trough consistent with the EDGES Cosmic Dawn signal:
  i. Blue curve: Maximum cooling rate is the adiabatic rate, but occurring earlier.
  ii. Red curve: Cooling rate both lower and earlier.
  iii. Magenta curve: Cooling rate not monotonically declining (i.e. there is a ‘preferred epoch’ of excess cooling).

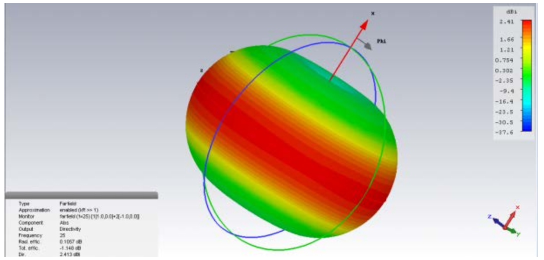
Models courtesy of Jordan Mirocha

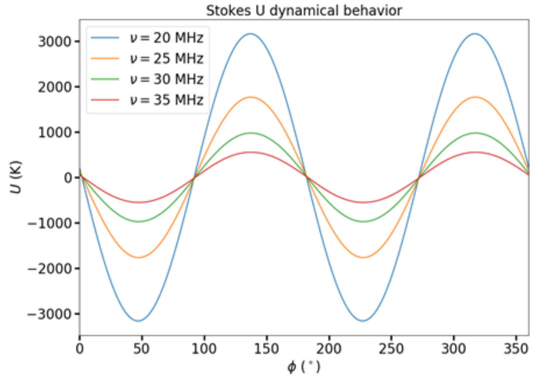
NESS
Network for Exploration and Space Science

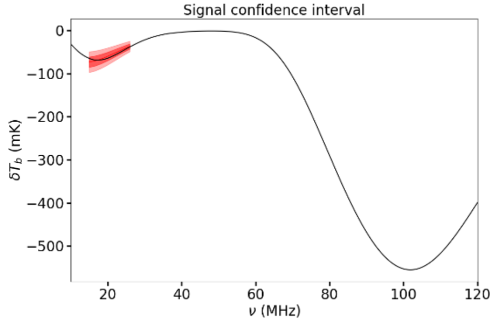
The Dark Ages Polarimetry PathfindER (DAPPER): A Space-based SmallSat Testbed

- DAPPER will be placed in proximity to NASA's Lunar Orbital Platform-Gateway to reduce Earth-based RFI.
- Operates over bandwidth of 15-30 MHz (93≥z≥46).
- Dual orthogonal ≈ 7-m tip-to-tip wire dipole antennas deployed successfully many times (e.g., WIND/WAVES).
- Low noise amplifiers & dual channel receiver to measure all 4 Stokes parameters. Based upon FIELDS instrument to be flown on Parker Solar Probe (collaboration with S. Bale, Berkeley).









Summary and Conclusions

- We developed a method which transforms the 21-cm signal extraction task from one where *absolute knowledge of system parameters* is required to one of *composing training sets where knowledge of the modes of variation* are used.
- Applying this method to simulated 21-cm experiment data sets using dual-polarized antennas, we extracted a wide variety of input signals with a 95% confidence error of $\lesssim$30 mK.
- The CTP ground-based prototype has tentatively detected the expected dynamic polarization signal from the Foreground.
- We are developing a SmallSat mission concept (DAPPER) to utilize both polarimetry and Pattern Recognition to detect the expected turning points in the Global 21-cm spectrum.