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

Spaced-based Extraction of the Global 21-cm Spectrum

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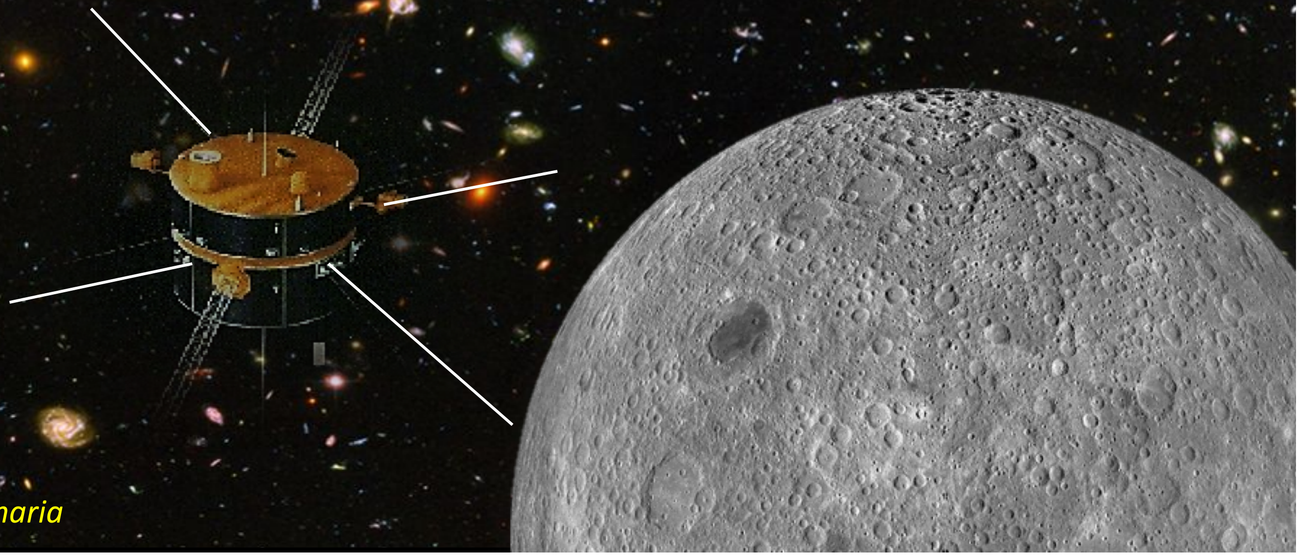

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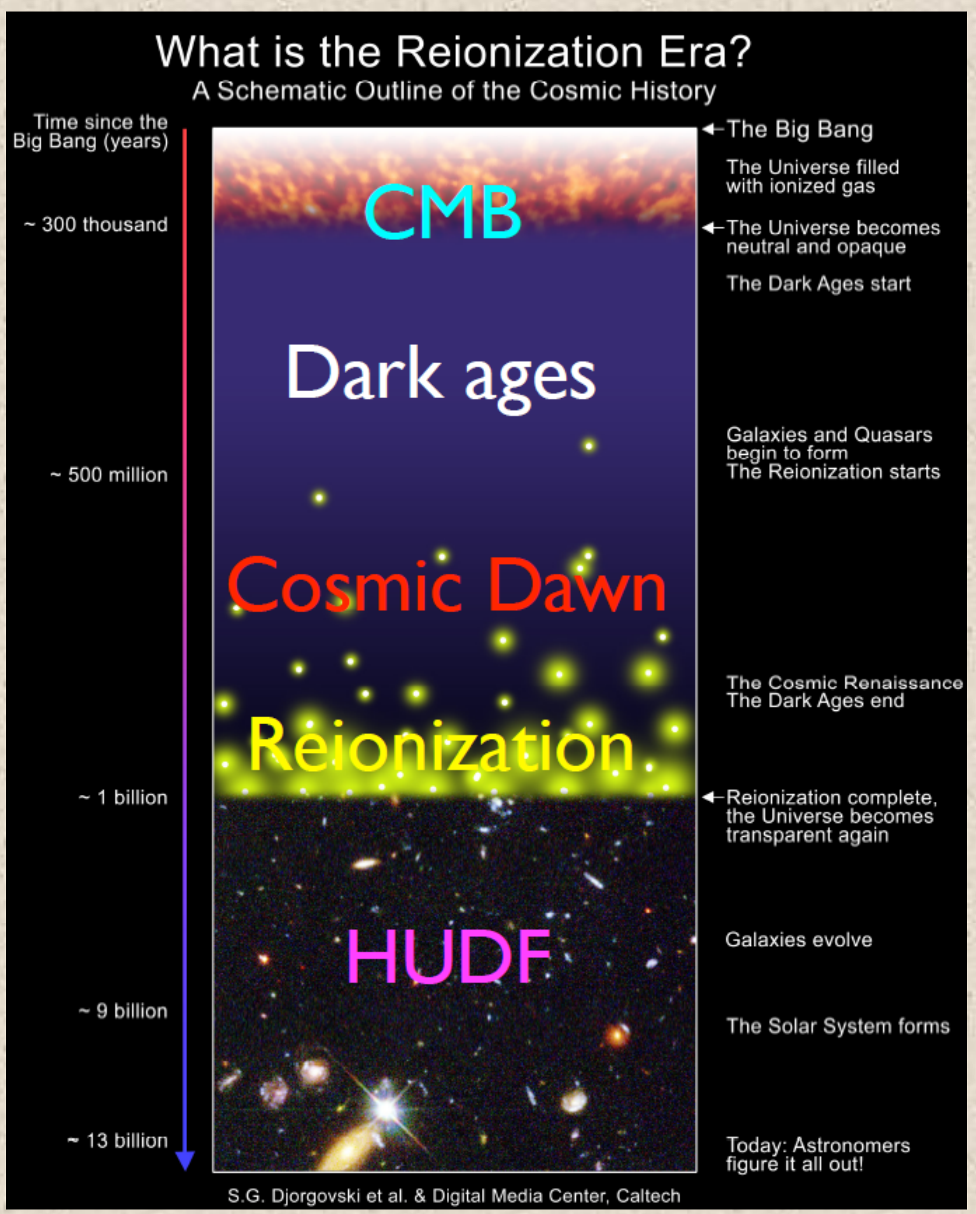
Current cosmic knowledge



S.G. Djorgovski et al. & Digital Media Center, Caltech

- We have measurements of
  - The early Universe from e.g. the CMB.
  - The Universe since about 1 billion years ago from distant galaxies by e.g. the Hubble Space telescope.

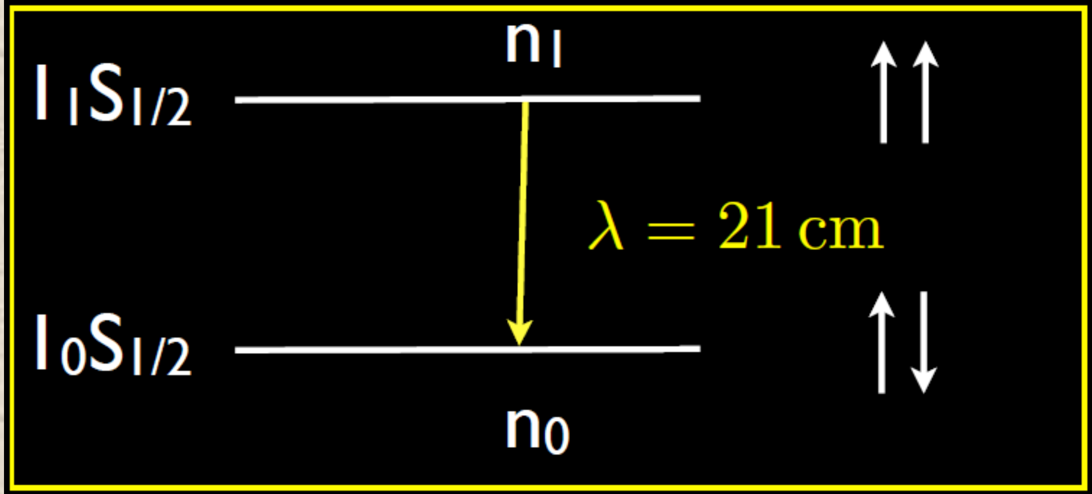
- But, we have little knowledge on the:
  - Dark Ages
  - Cosmic Dawn
  - Onset of reionization

- During the Dark Ages, the Universe consisted almost entirely of neutral hydrogen.

21-cm hyperfine transition

$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001 \text{ Hz}$$

Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

$$n_1/n_0 = 3\exp(-h\nu_{21\text{cm}}/kT_s)$$

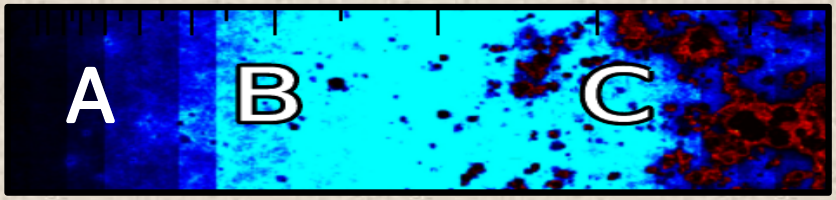
Useful numbers:

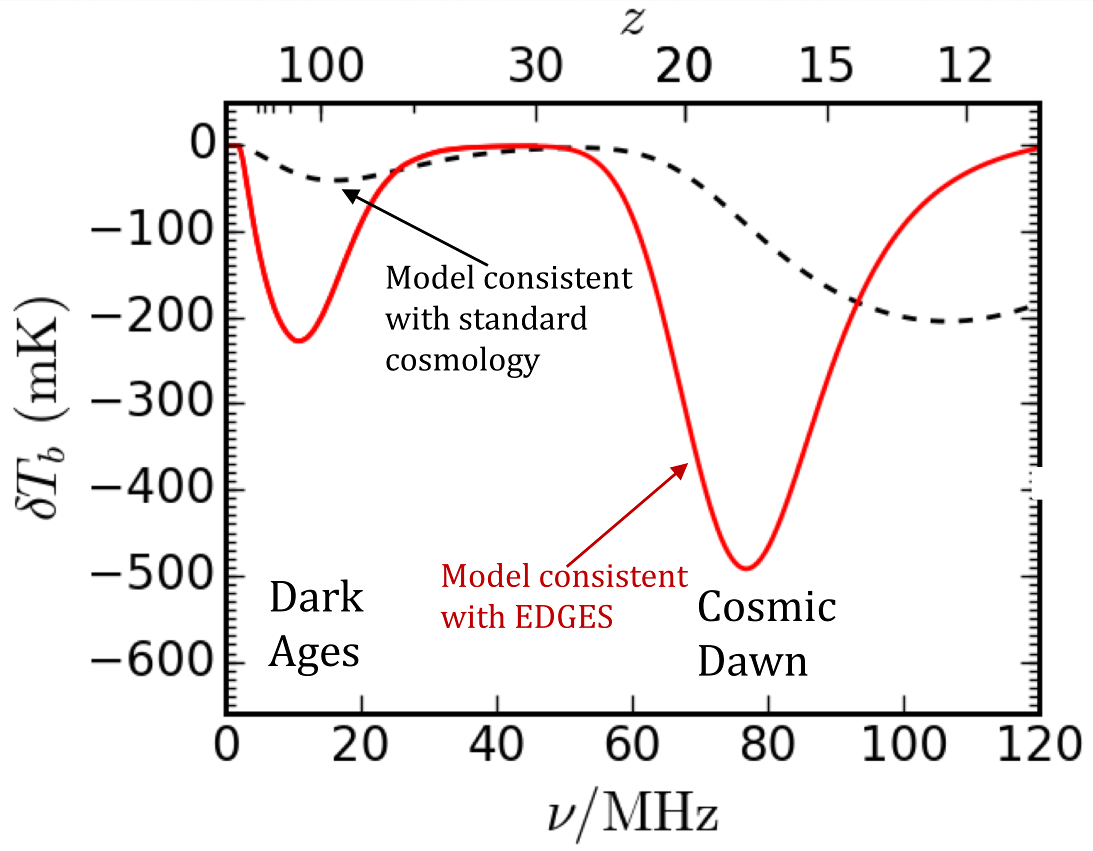
$200 \text{ MHz} \rightarrow z = 6$
$100 \text{ MHz} \rightarrow z = 13$
$70 \text{ MHz} \rightarrow z \approx 20$

$t_{\text{Age}}(z = 6) \approx 1 \text{ Gyr}$
$t_{\text{Age}}(z = 10) \approx 500 \text{ Myr}$
$t_{\text{Age}}(z = 20) \approx 150 \text{ Myr}$

Slide credit: J. Burns

Global 21-cm signal from the first luminous objects





Spectral Features:

A: Dark Ages (test of standard cosmological model)

B: First stars ignite (Cosmic Dawn)

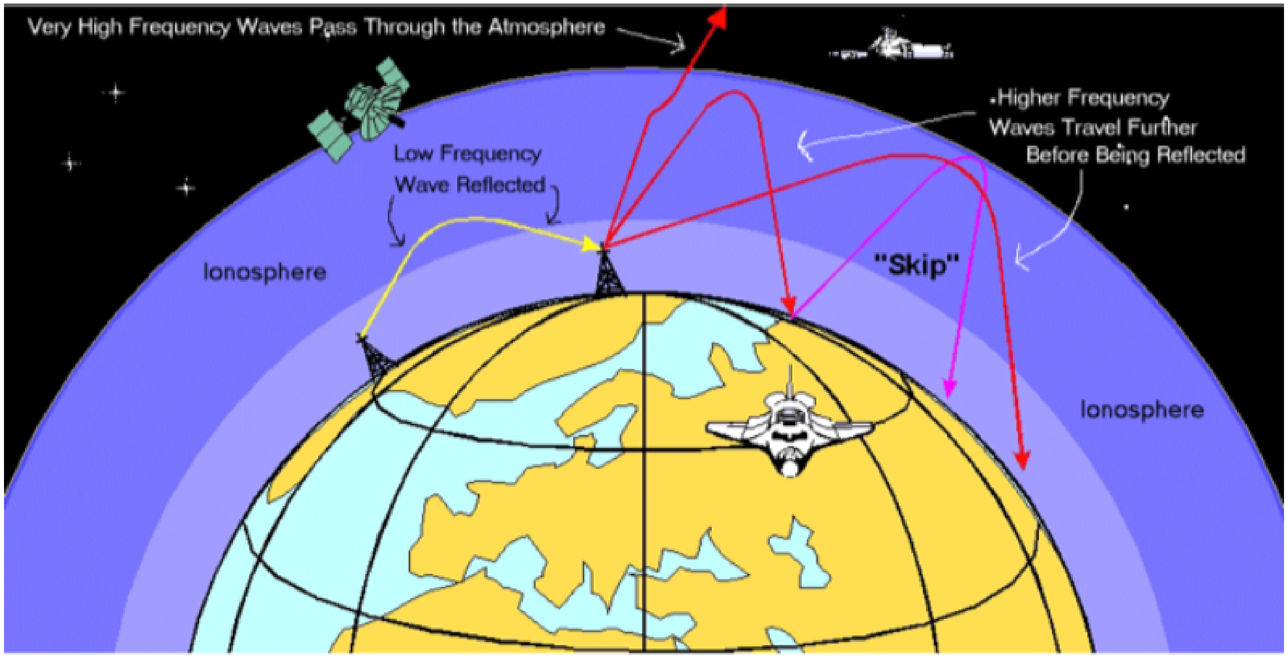
C: Black hole accretion begins

$$\delta T_b(z) = 27 x_{\mathrm{HI}}(z) \left(1 - \frac{T_{\mathrm{CMB}}(z)}{T_{\mathrm{s}}(z)}\right) \left(\frac{1+z}{10}\right)^{1/2}$$

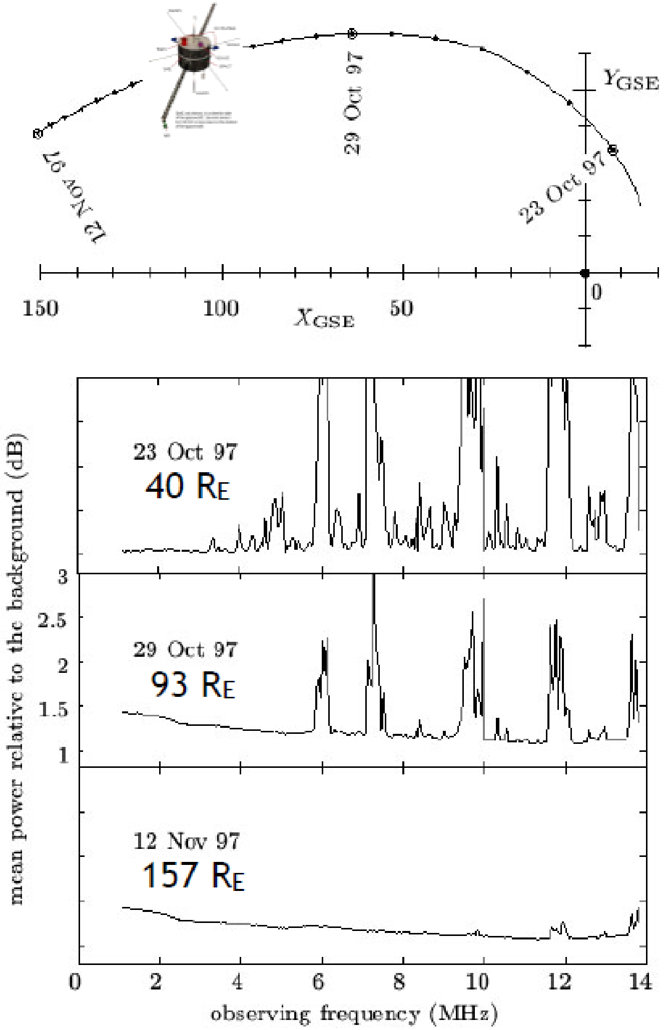
Models courtesy of Jordan Mirocha

Near Earth Radio Environment

No place on/near Earth is Dark
at Low Frequencies (LF radio "smog")

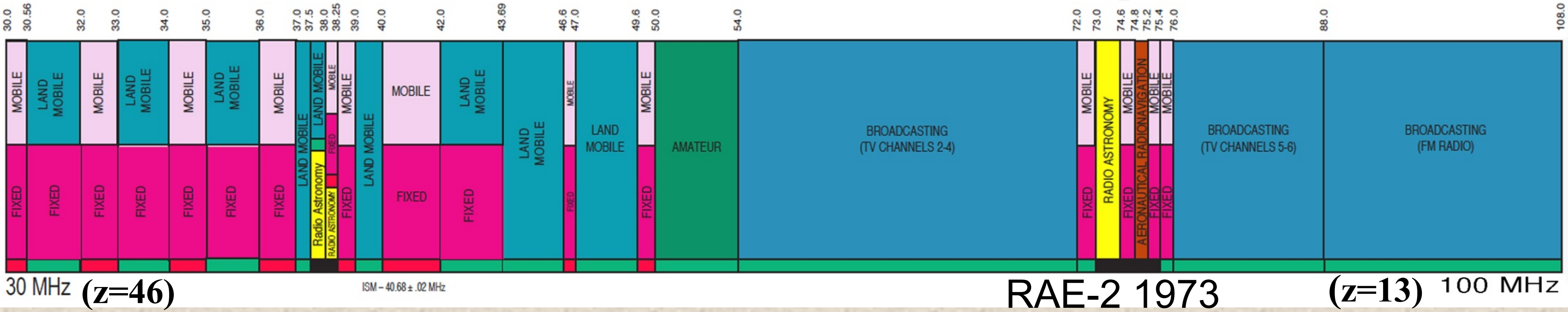


Slide courtesy of C. Cecconi, Observatoire de Paris



24h averages from Wind/WAVES

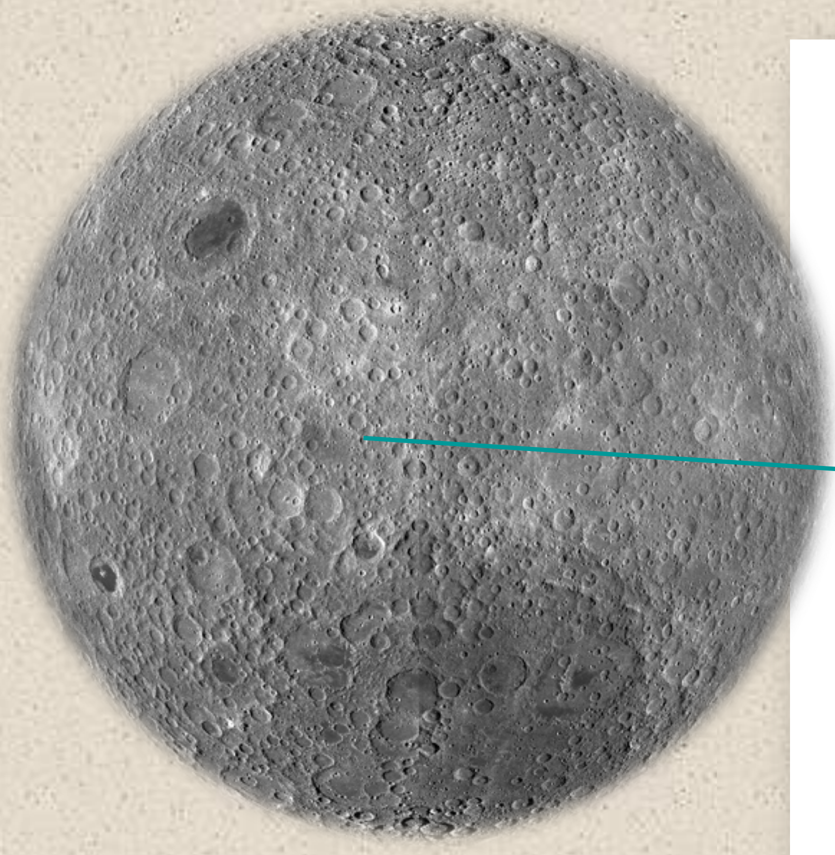
Lunar Farside: No RFI or Ionosphere!

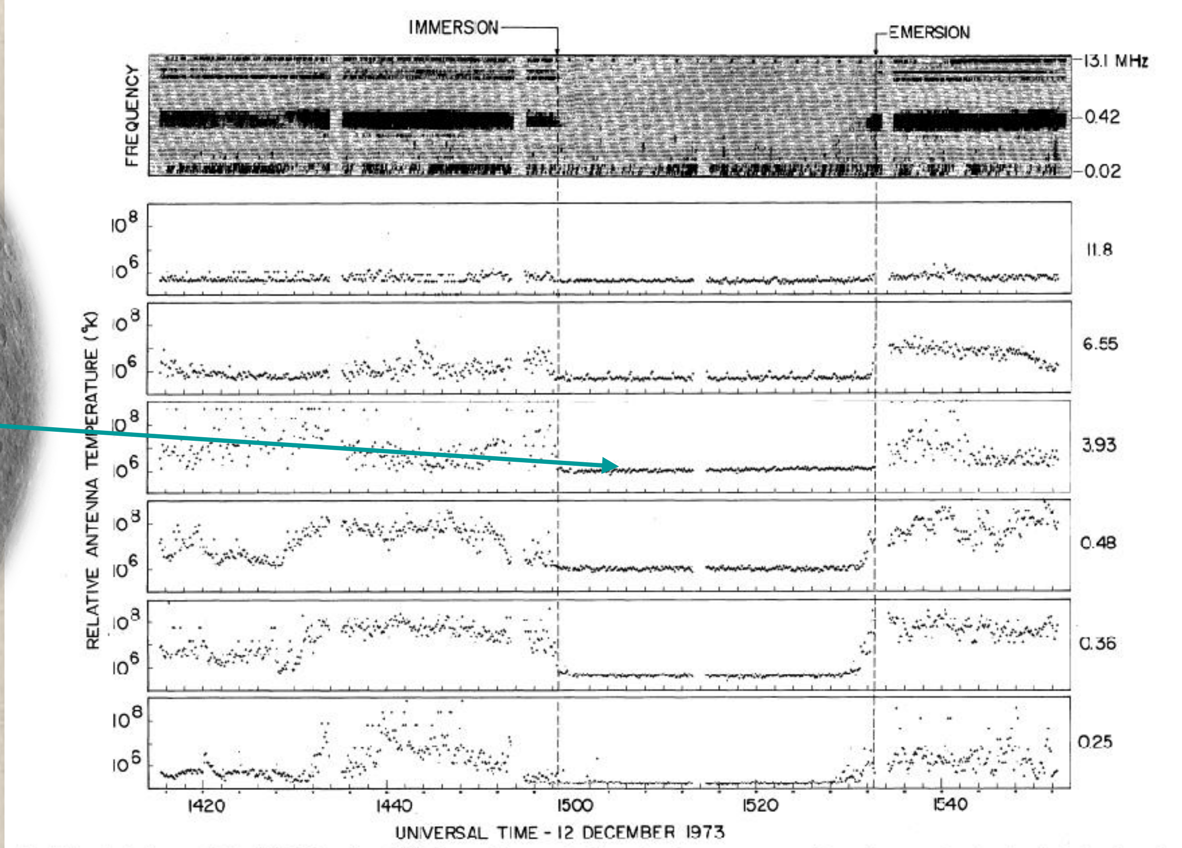


(z=46)

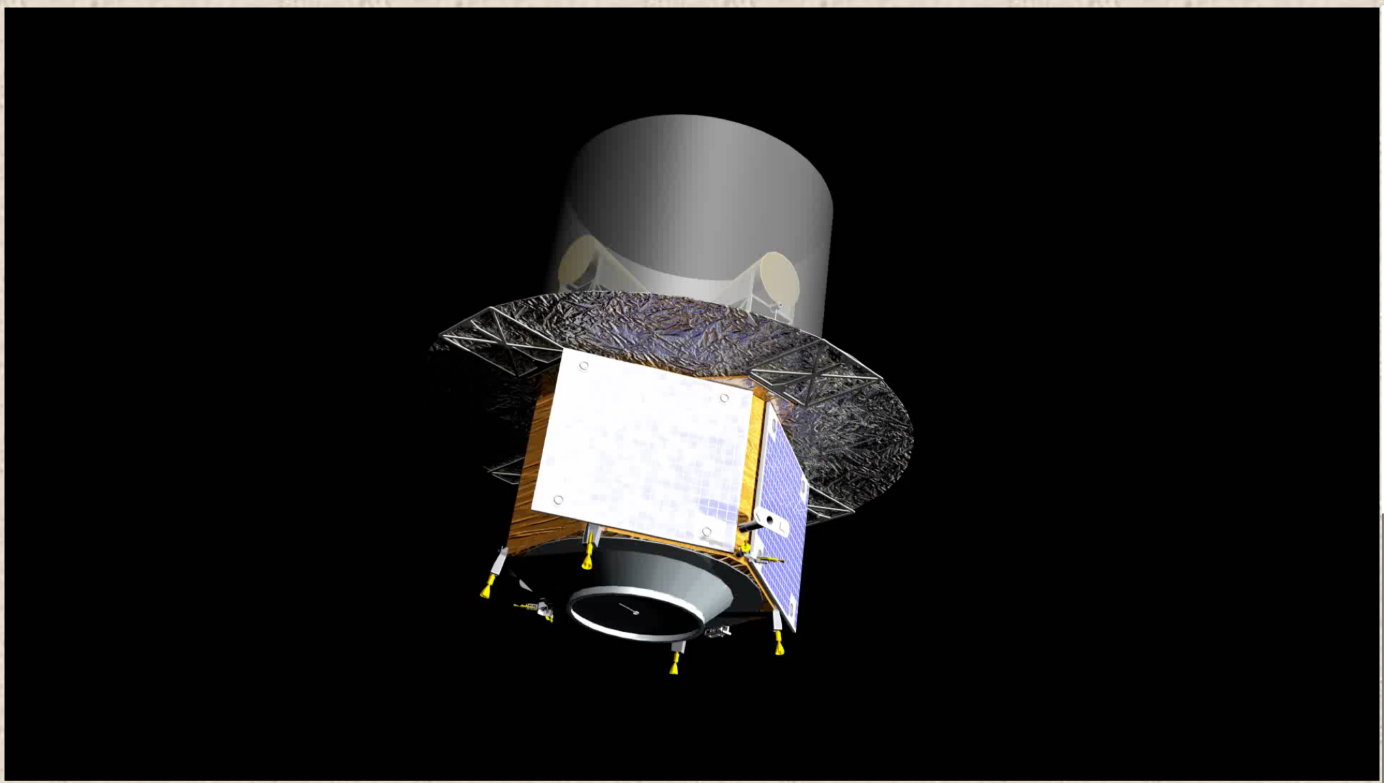
RAE-2 1973

(z=13)



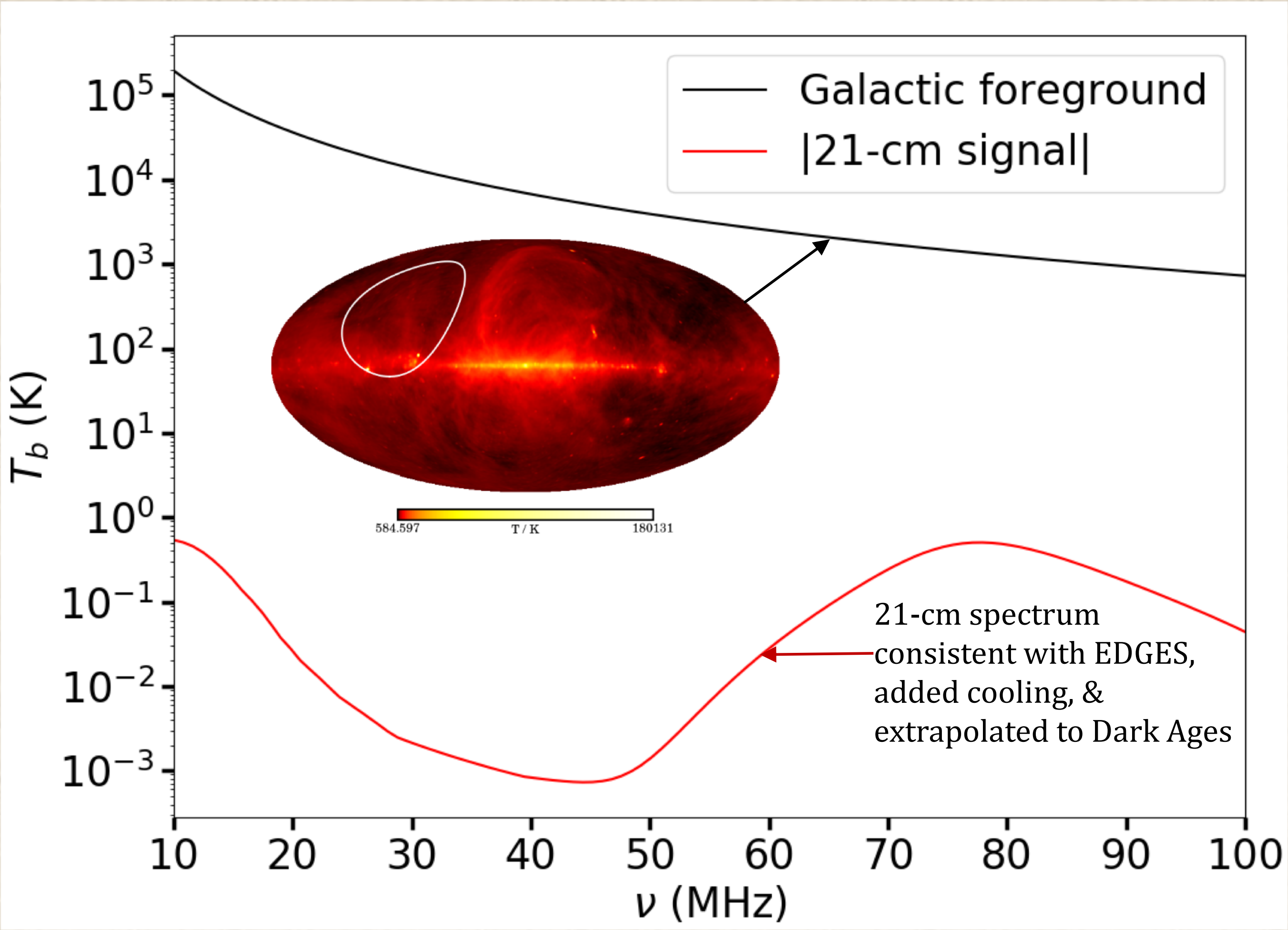


Dark Ages Radio Explorer (DARE)



- Space mission concept that uses dual polarization bicone antennas to measure the global 21-cm signal from the lunar farside.
- In this way, it avoids Earth-based challenges like ionospheric effects and RFI as well as radio solar emissions.
- See also the website of our SSERVI team NESS (Network for Exploration and Space Sciene): https://www.colorado.edu/ness/

Challenges of the Global 21-cm Observation



21-cm spectrum consistent with EDGES, added cooling, & extrapolated to Dark Ages

Foreground Characteristics

- Spectrally smooth
- Spatial structure
- Polarized

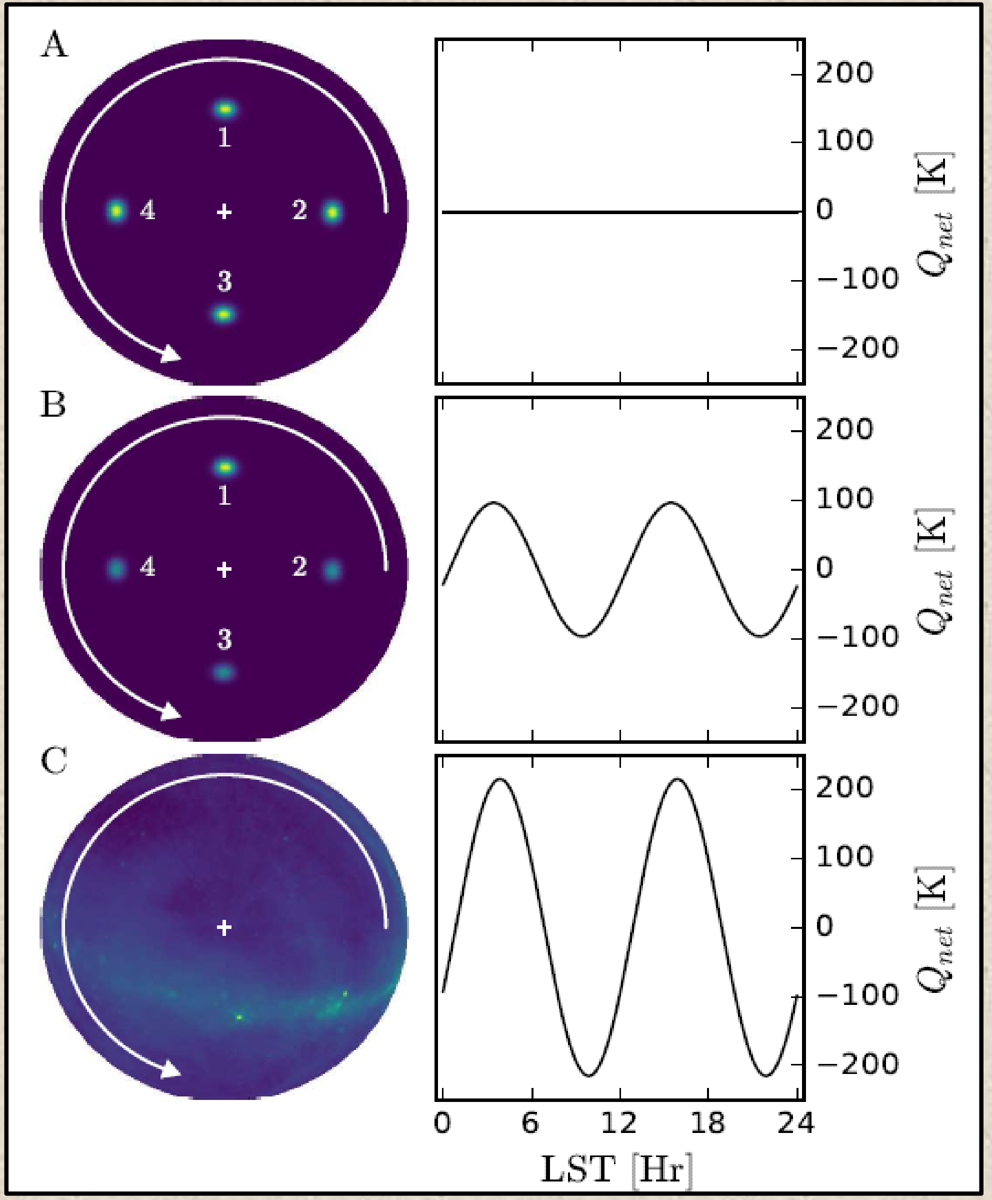
Signal Characteristics

- Spectral structure
- Spatially isotropic
- Unpolarized

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

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

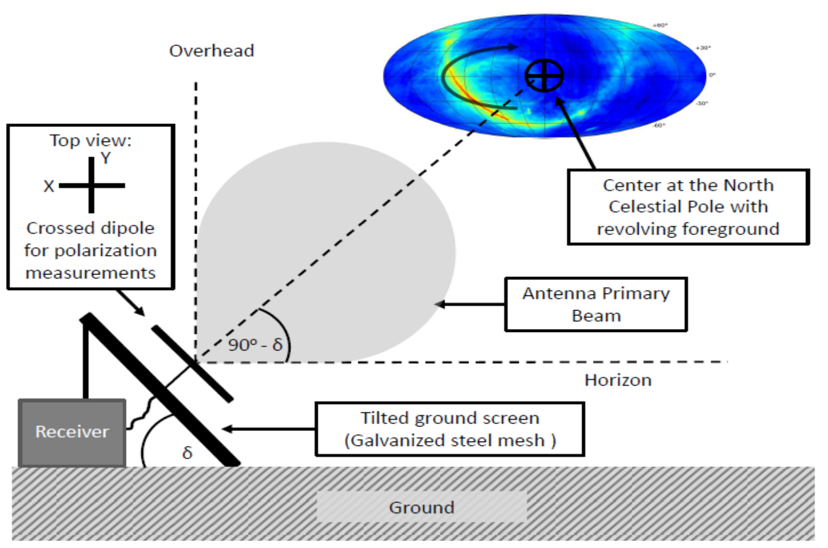
Experimental design: Induced polarization Novel technique to break degeneracies



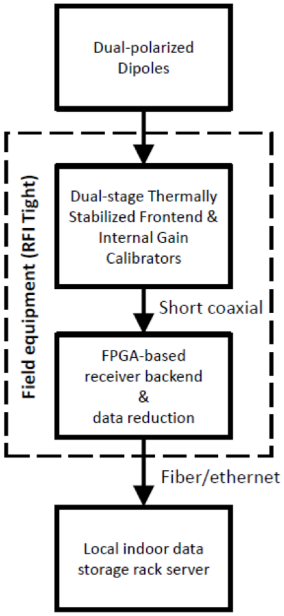
- Left: The observed source distribution where the cross is the pointing center and the white arrow is the rotation direction of the antenna.
- Right: The net *Q* Stokes vector as measured by a symmetric Gaussian beam at 60 MHz.
- *Case A*: Four identical sources symmetric about the boresight resulting in a net zero polarization vector under rotation.
- *Case B*: Four sources symmetric about the boresight where source one is enhanced in intensity resulting in a non-zero net polarization vector.
- *Case C*: The real sky resulting in a non-zero net polarization vector.
- See Nhan et al. (2017) for further details.

The Cosmic Twilight Polarimeter (CTP): Dynamic Polarimetry Testbed

Nhan, Bradley, & Burns (2017)



System Block Diagram


Dual-polarized Dipoles

Field equipment (RFI Tight)

Dual-stage Thermally Stabilized Frontend & Internal Gain Calibrators

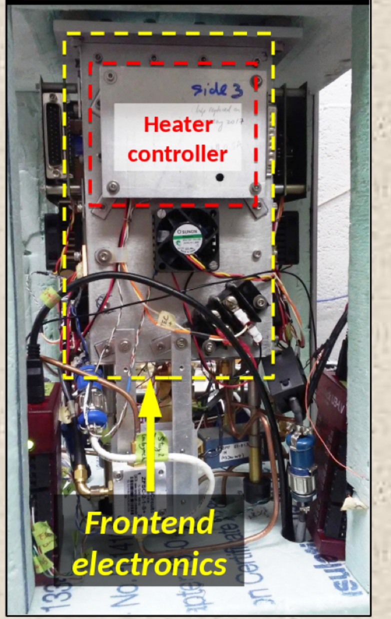
Short coaxial

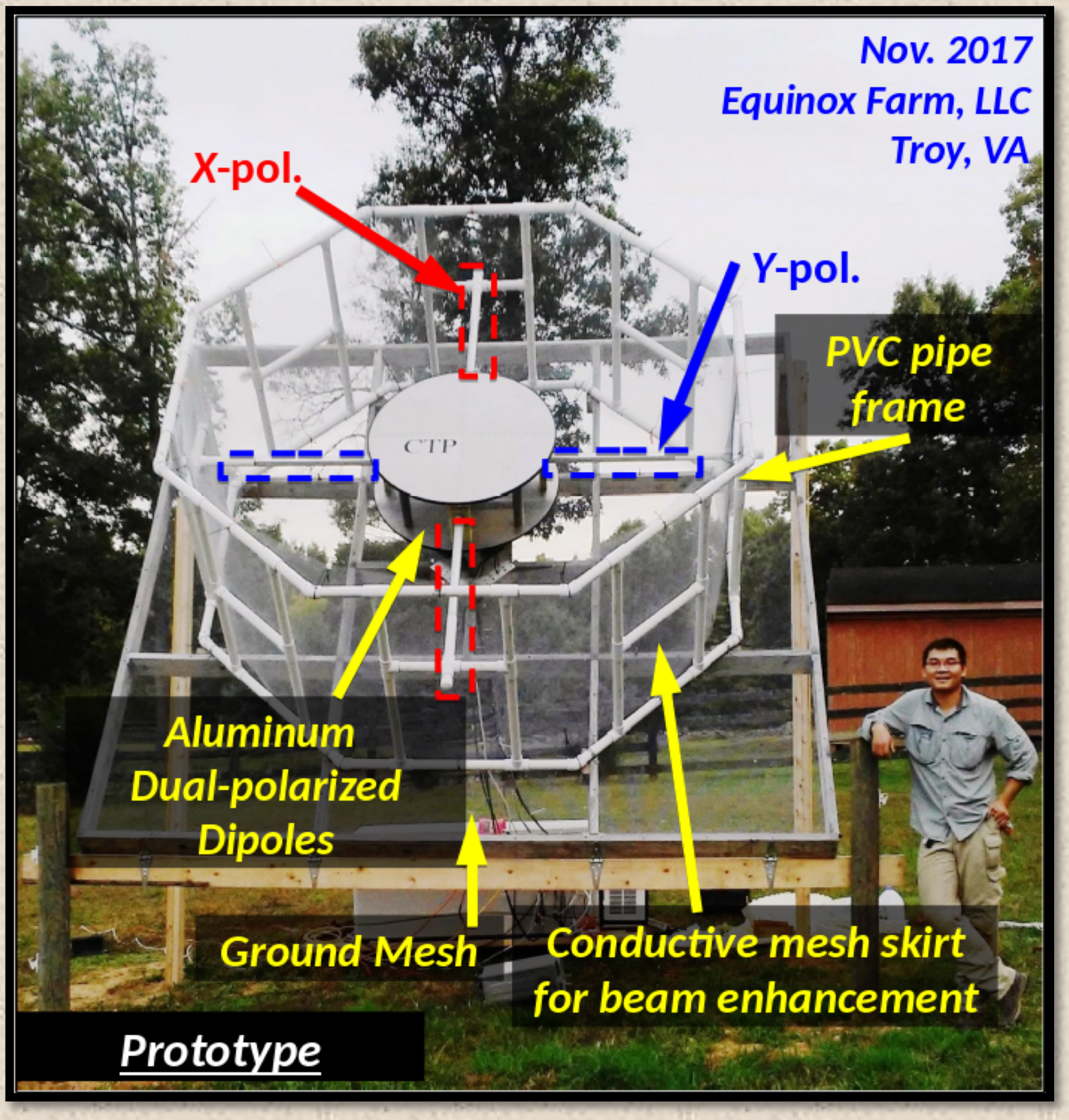
FPGA-based receiver backend & data reduction

Fiber/ethernet

Local indoor data storage rack server

Dual-stage thermal control





Operates over 60-80 MHz

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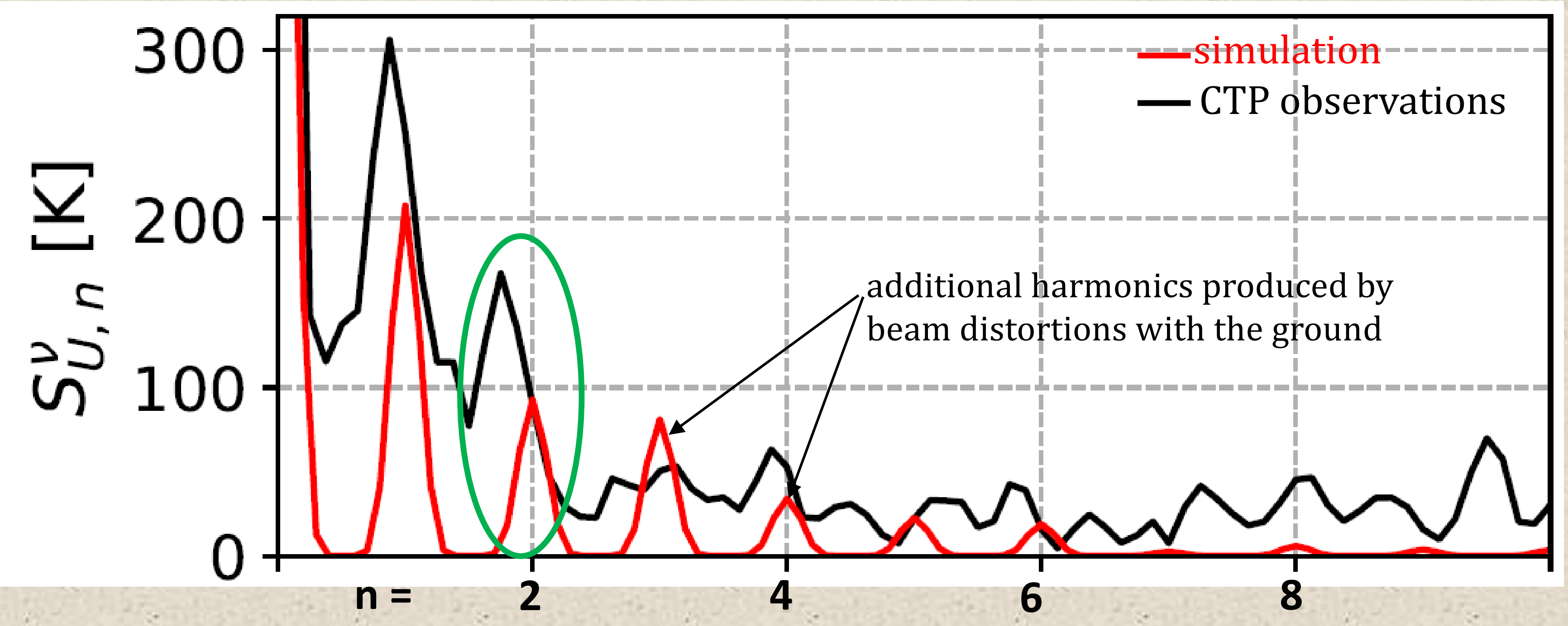
Initial CTP Results

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



additional harmonics produced by beam distortions with the ground

- 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.

Singular Value Decomposition (SVD)

$$\underbrace{\boldsymbol{M}} = \underbrace{\boldsymbol{U}}\boldsymbol{\Sigma}\boldsymbol{V}^T$$

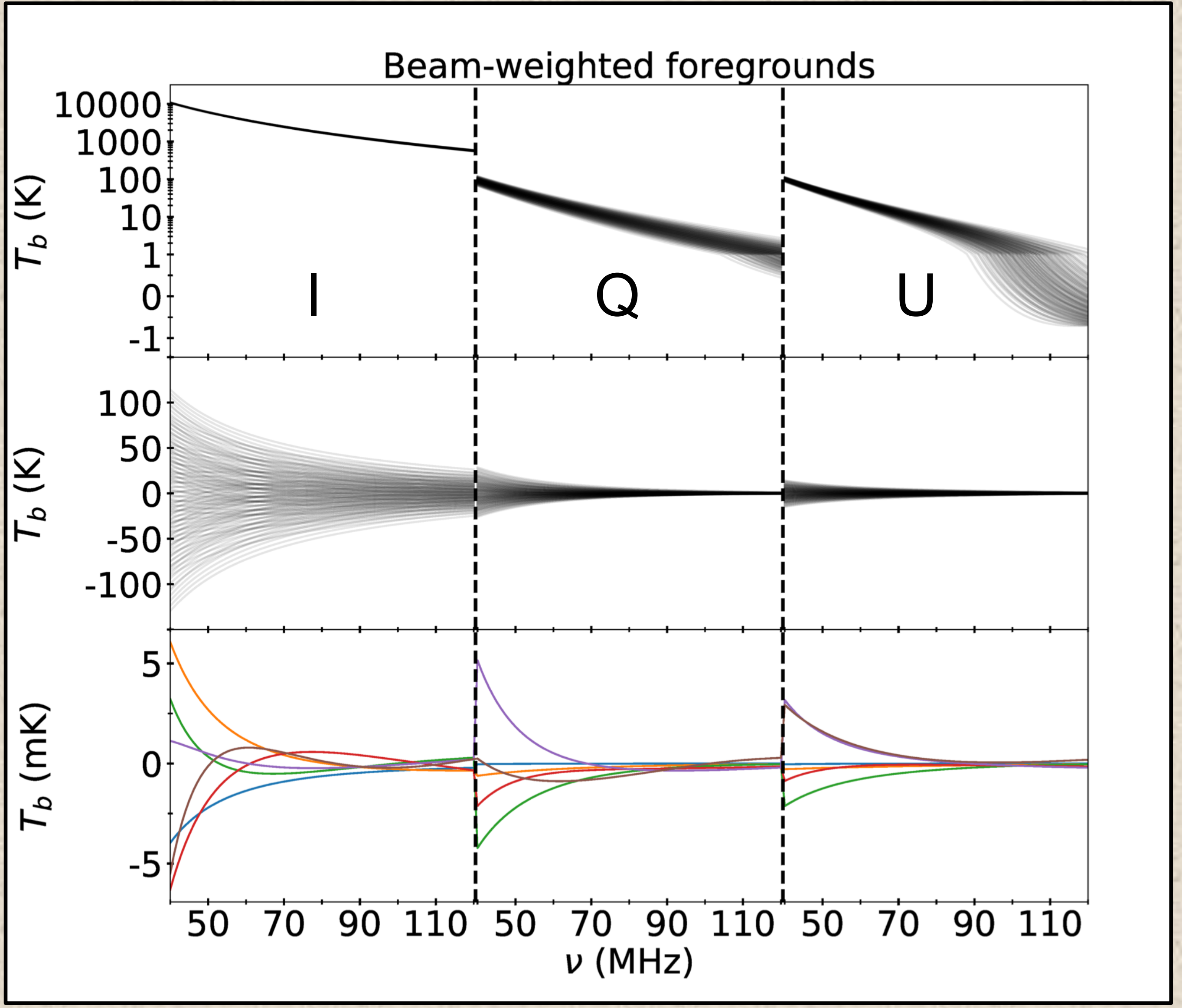
Training Set:
$(N_{channel} \times N_{curves})$

Ordered basis functions:
$(N_{channel} \times N_{channel})$

- SVD computes and orders the orthogonal modes of the N_{curves} curves of the training set, $\boldsymbol{M}$, by importance.
- $\boldsymbol{\Sigma}$ is a diagonal matrix containing the importance of the modes (square root of eigenvalues of $\boldsymbol{M}\boldsymbol{M}^T$).

Experimental design: Induced polarization
Including the Stokes parameters into the likelihood

Tauscher et al. (2018)

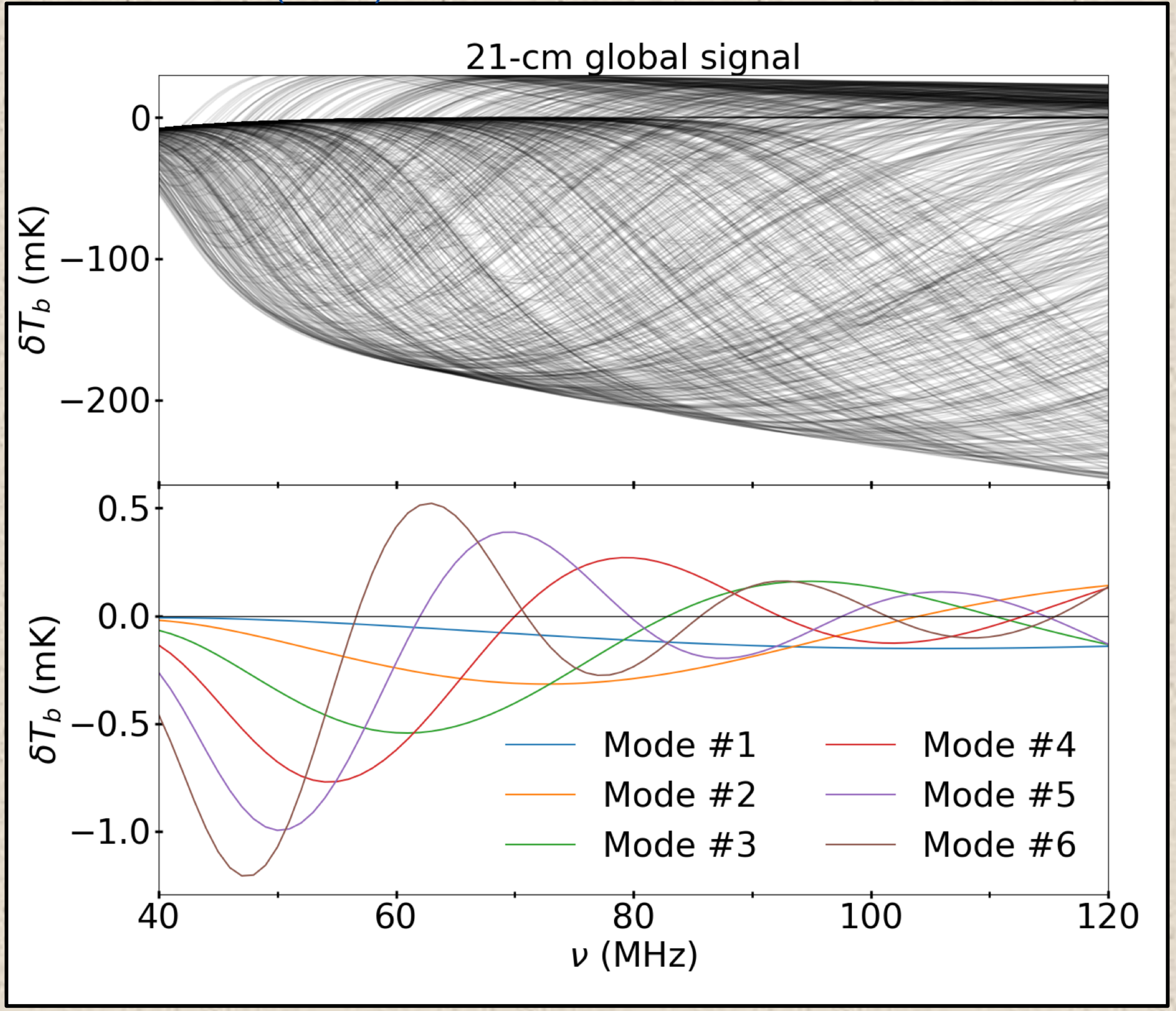


- Beam-weighted foreground training set for a single rotation angle about one of the 4 antenna pointing directions (top), the same training set with its mean subtracted (middle), and the first 6 SVD basis functions obtained from the training set (bottom).

- The different rotation angles about the antenna pointing direction are part of the same training set so that SVD can pick up on angle-dependent structure and imprint it onto the basis functions.

Global 21-cm signal training set

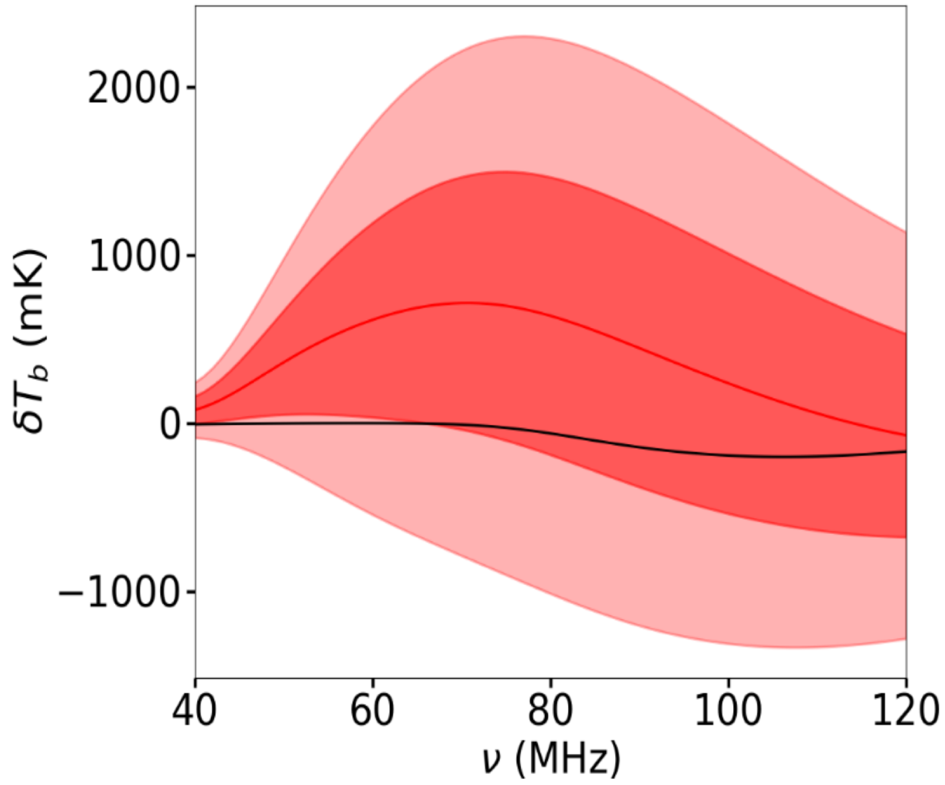
Tauscher et al. (2018)



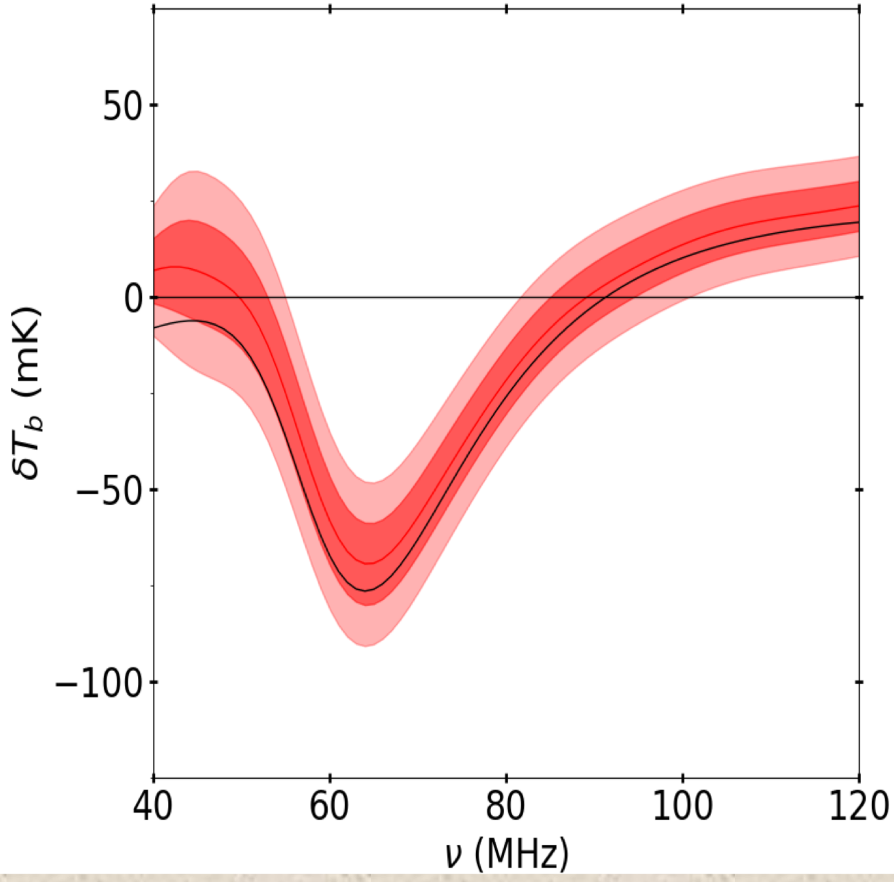
- The signal training set used for our analysis was generated by running the *ares* code 7 × 105 times within reasonable parameter bounds in order to fill the frequency band.
- The top panel shows a thinned sample of that set (black curves). The SVD modes are ordered from most to least important.
- The modes are normalized so that they yield 1 when divided by the noise level, squared, and summed over frequency, antenna pointing, and rotation angles about the antenna pointing.

Importance of using polarization data

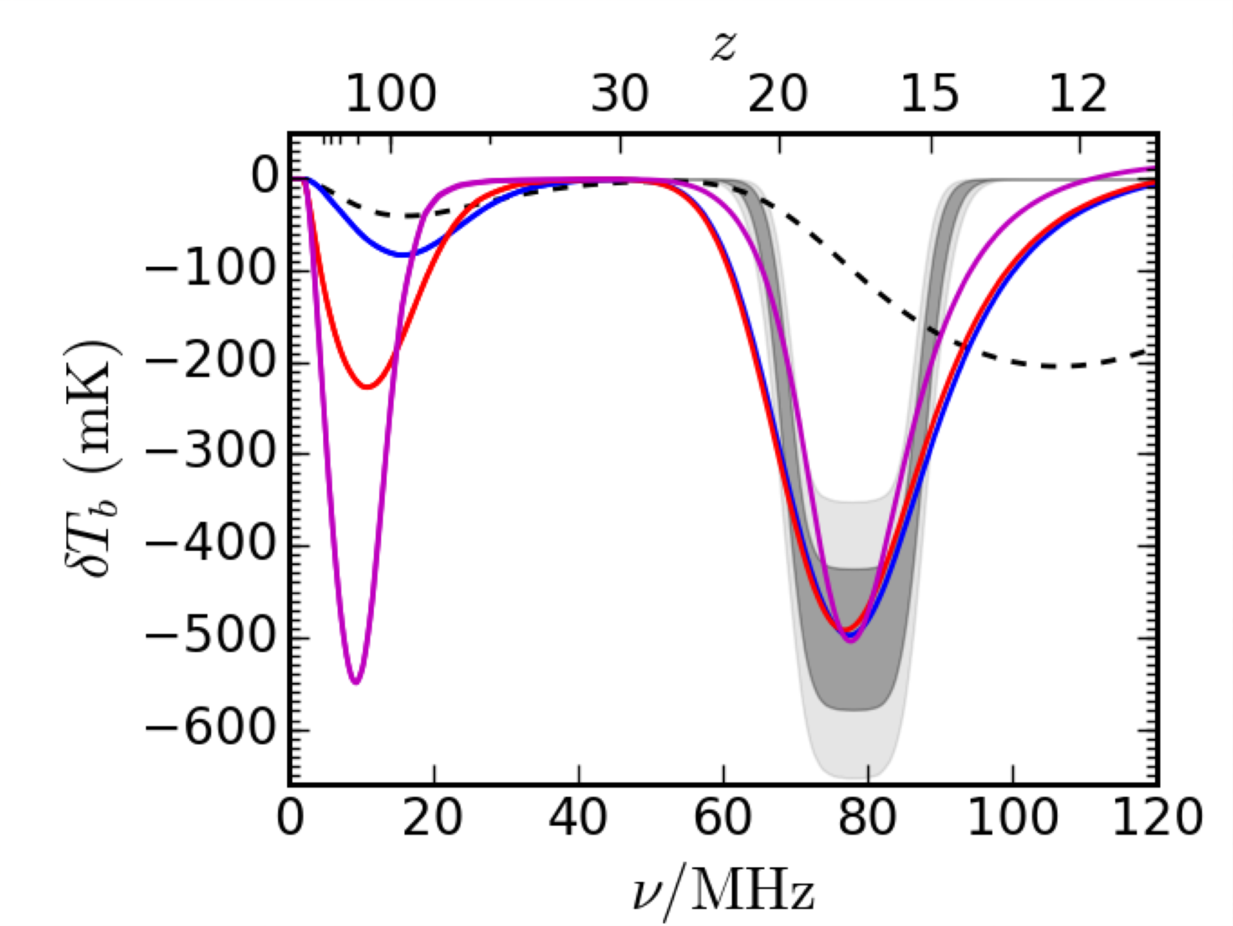
Stokes I Only



All 4 Stokes Parameters



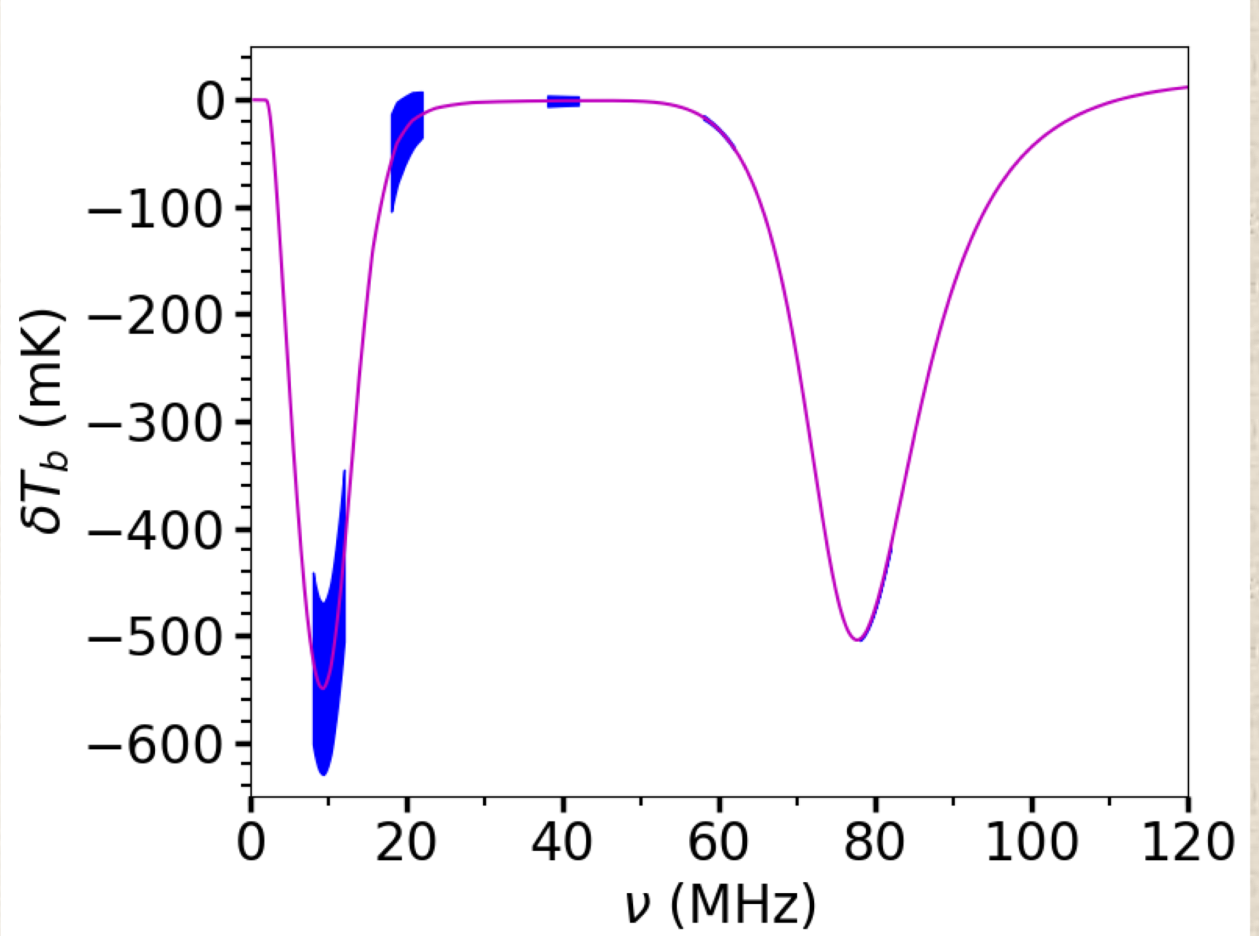
Exploring the Dark Ages



Models courtesy of Jordan Mirocha

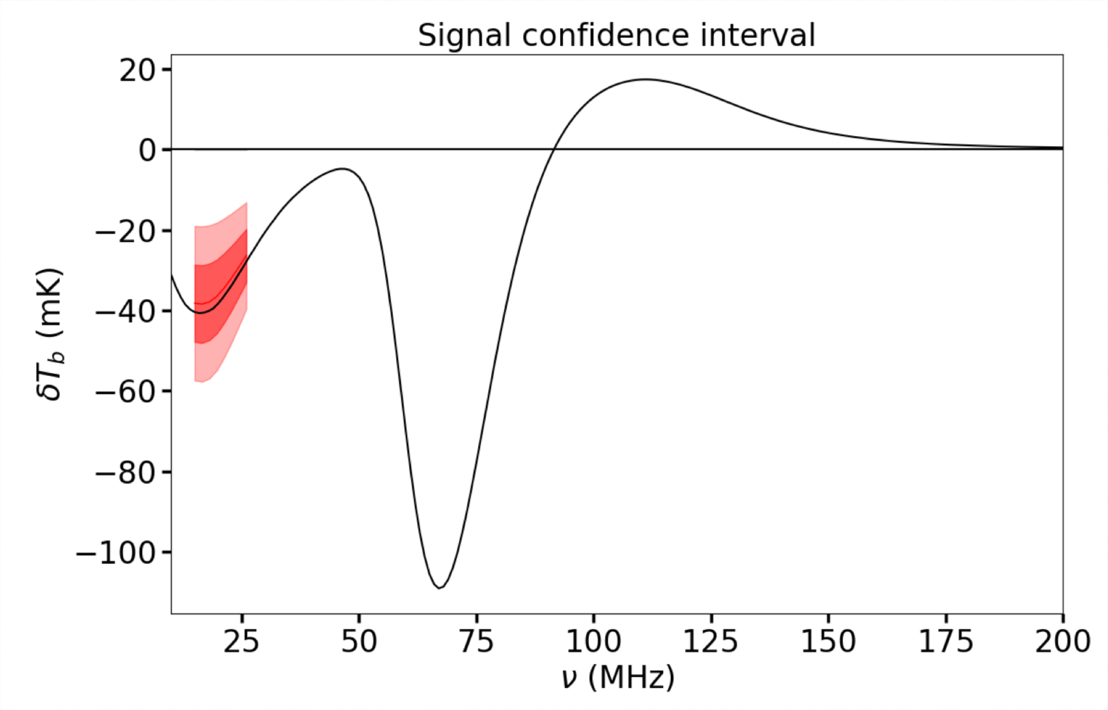
- **68 and 95% (dark and light gray) bands:** EDGES measurements of **Cosmic Dawn.**
- **Black, dashed curve:** Example of the **standard** astrophysical models ***inconsistent with EDGES results***.
- EDGES results *require exotic physics* such as e.g. interactions between baryons and dark matter particles.
- *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).

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



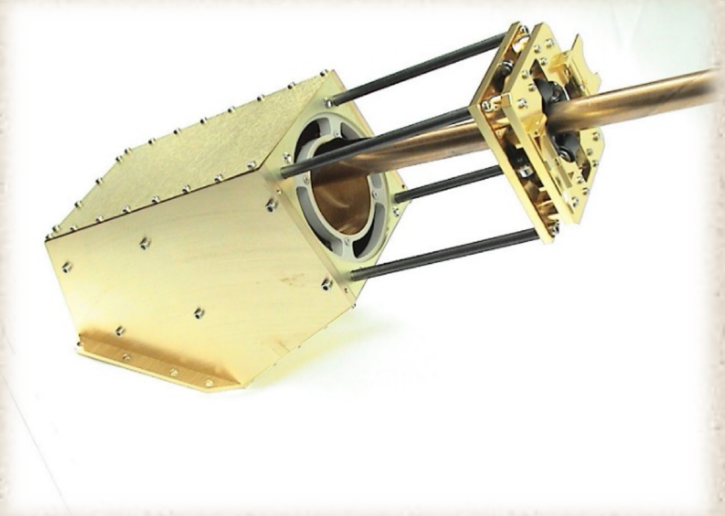
- DAPPER would be placed in a 50×125 km low lunar orbit.
- Operate over 4 narrow (5 MHz) bands from 10-60 MHz.
- Simulations for DAPPER using our Pattern Recognition Pipeline. Blue bands are 68% uncertainties.

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



Simulations for DAPPER using instead a standard 21-cm model.

- Dual orthogonal 7-14-m 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.

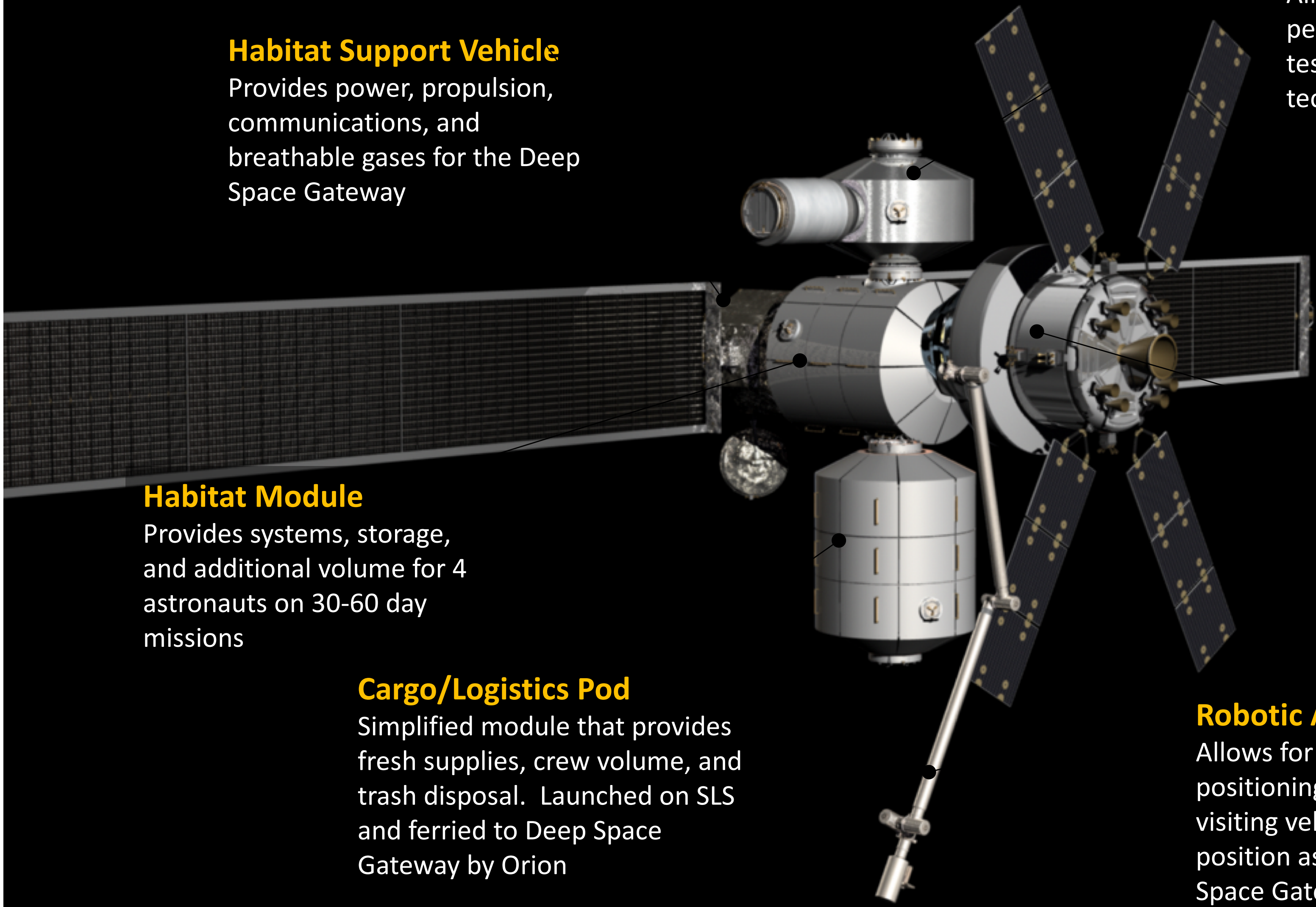


Possible antenna and deployer (courtesy of S. Bale, UC-Berkeley)

Conclusions

- A challenge of extracting the global 21-cm is the large foregrounds.
- However, unlike the foregrounds the signal is spatially uniform, has well-characterized spectral features, and is unpolarized.
- We benefit from these differences in our novel approach for signal extraction and physical parameter constraints, using an SVD/MCMC pipeline.
- We obtain a highly significant improvement by using a pioneering induced polarization technique. Applying this method to simulated 21-cm 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 also working on running our pipeline on current/ongoing ground based data from EDGES and CTP.
- We are developing a SmallSat mission concept (DAPPER) to utilize both polarimetry and Pattern Recognition/Information Criteria/MCMC to detect the expected absorption features in the Global 21-cm spectrum.

Lunar Orbital Platform-Gateway



EVA Module
Allows astronauts to perform spacewalks and test advanced EVA technology

Habitat Support Vehicle
Provides power, propulsion, communications, and breathable gases for the Deep Space Gateway

Habitat Module
Provides systems, storage, and additional volume for 4 astronauts on 30-60 day missions

Orion Spacecraft
Brings astronauts to and from the DSTH. Provides advanced functionality to Deep Space Gateway during crew visits

Cargo/Logistics Pod
Simplified module that provides fresh supplies, crew volume, and trash disposal. Launched on SLS and ferried to Deep Space Gateway by Orion

Robotic Arm
Allows for berthing and re-positioning of new elements and visiting vehicles. Used during EVA to position astronauts around Deep Space Gateway