Dark Cosmology: Searching for Dark Matter in the Dark Ages using the Global 21-cm Spectrum

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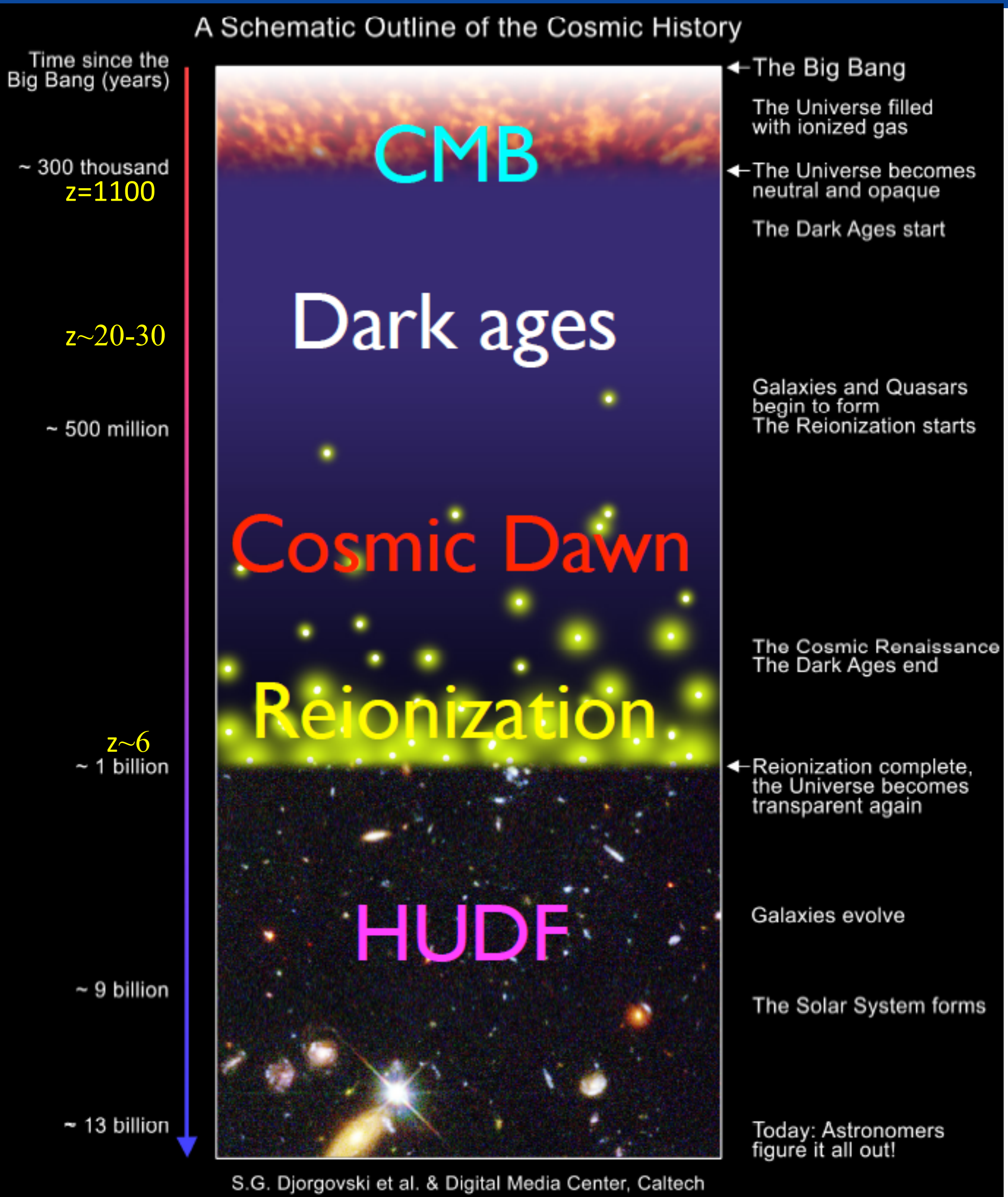
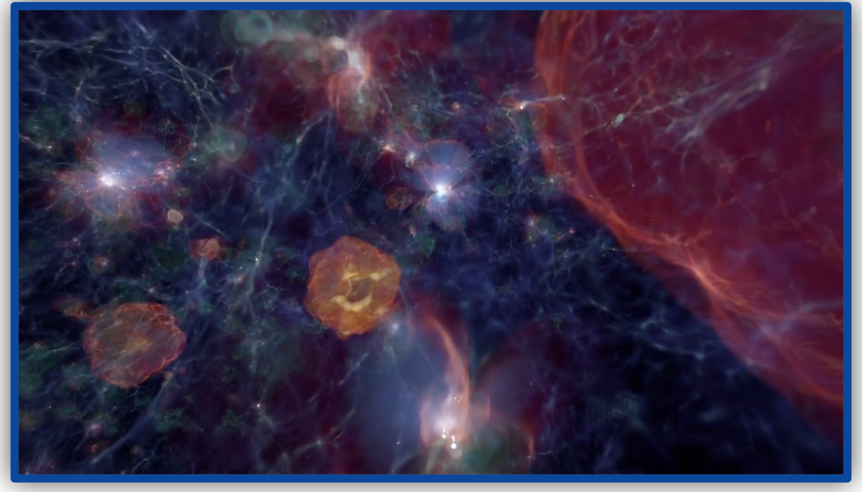
Identification of Dark Matter 2018, Brown University, 26 July 2018

The First Half-Billion Years



The First Stars

M. Norman, B. O'Shea et al.



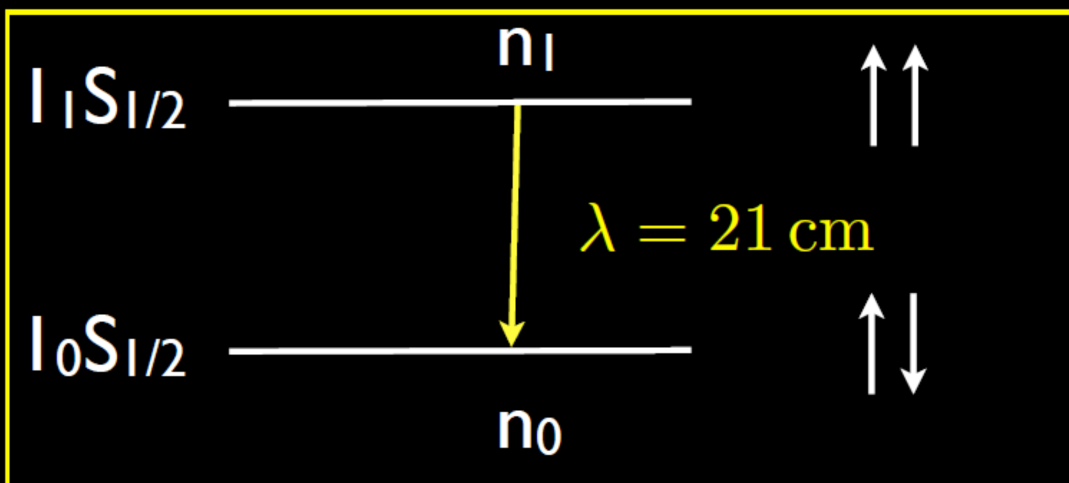
Science Questions

- When did the First Stars ignite and what were their characteristics?
- When did the first Black Holes begin accreting and what were their characteristics?
- What was the Reionization history of the early Universe?
- Is there any evidence for exotic physics, e.g. Dark Matter in the Dark Ages?

The 21-cm Hyperfine Line of Neutral Hydrogen

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

Hyperfine transition of neutral hydrogen



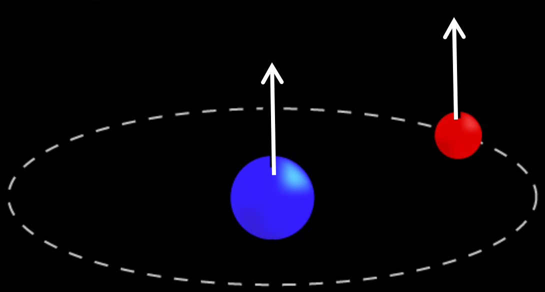
Spin temperature describes relative occupation of levels

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

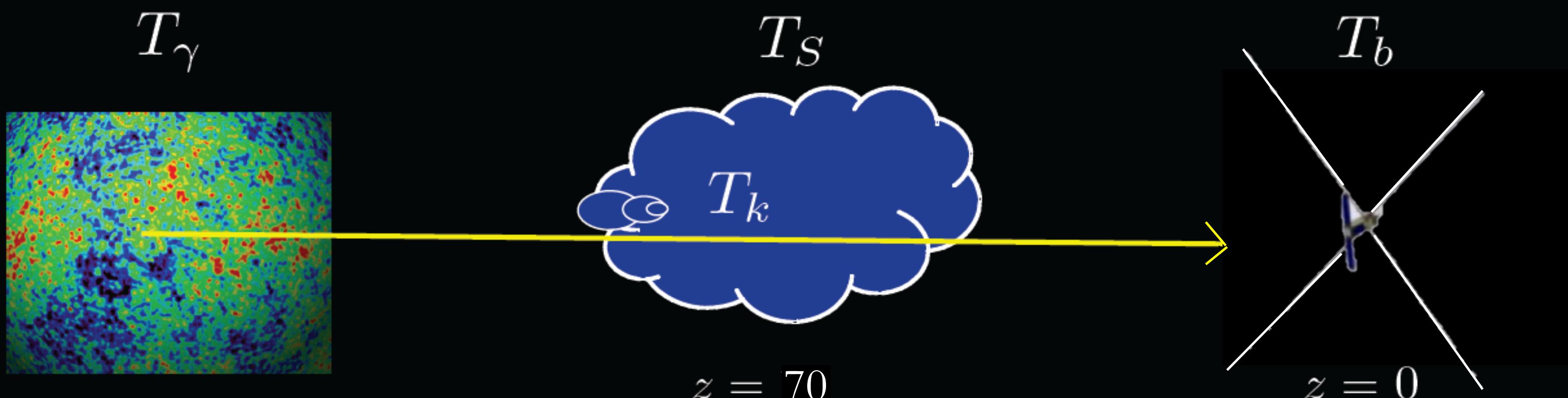
Useful numbers:

$$200 \text{ MHz} \rightarrow z = 6$$
$$100 \text{ MHz} \rightarrow z = 13$$
$$70 \text{ MHz} \rightarrow z \approx 20$$
$$40 \text{ MHz} \longrightarrow z \approx 35$$

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



The 21-cm Line in Cosmology



$z = 70$

$\nu = 1.4\,\mathrm{GHz}$

$z = 0$

$\nu = 20\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature (P=k$T_b\Delta\nu$)

$$T_b = 27 x_{\mathrm{HI}} (1+\delta_b) \left(\frac{T_S - T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

spin temperature set by different mechanisms:

- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect

Courtesy of J. Pritchard

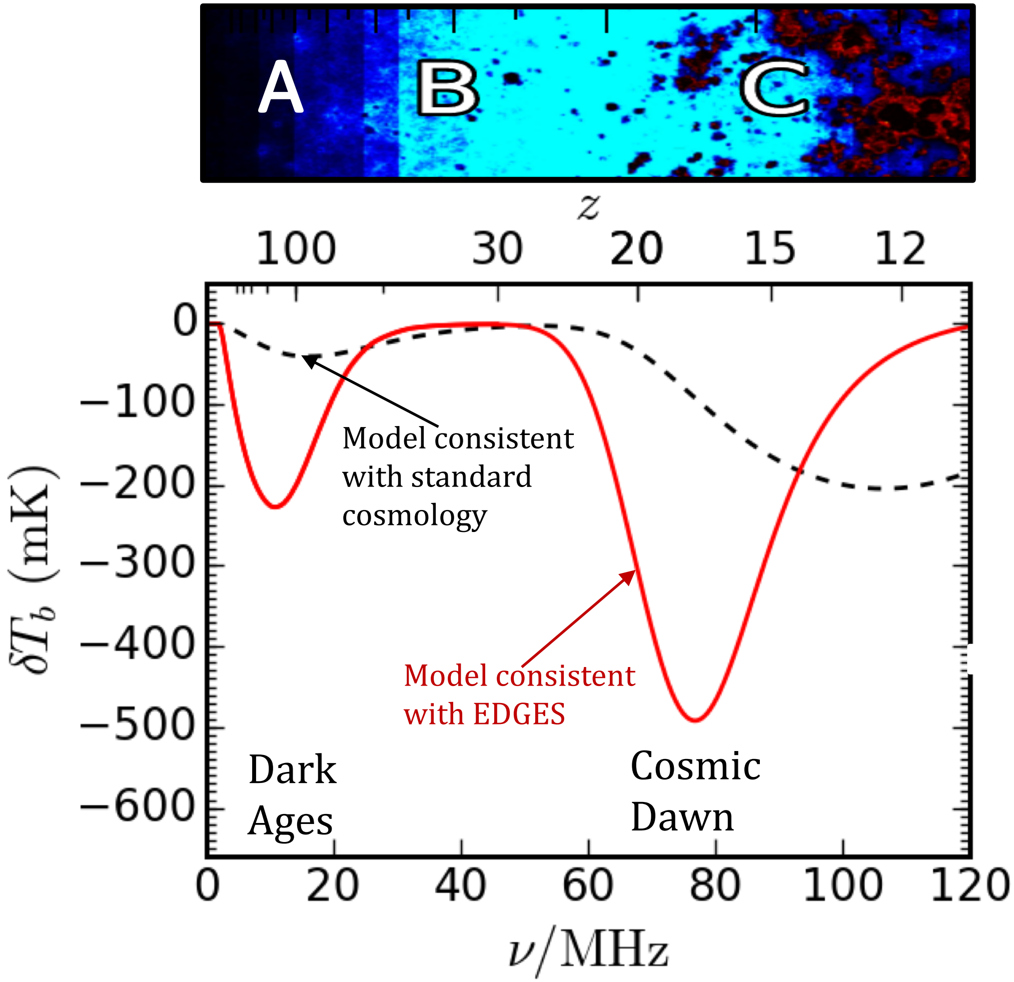
What is the 21-cm Global signal?

Spectral Features:

A: Dark Ages: test of standard cosmological model

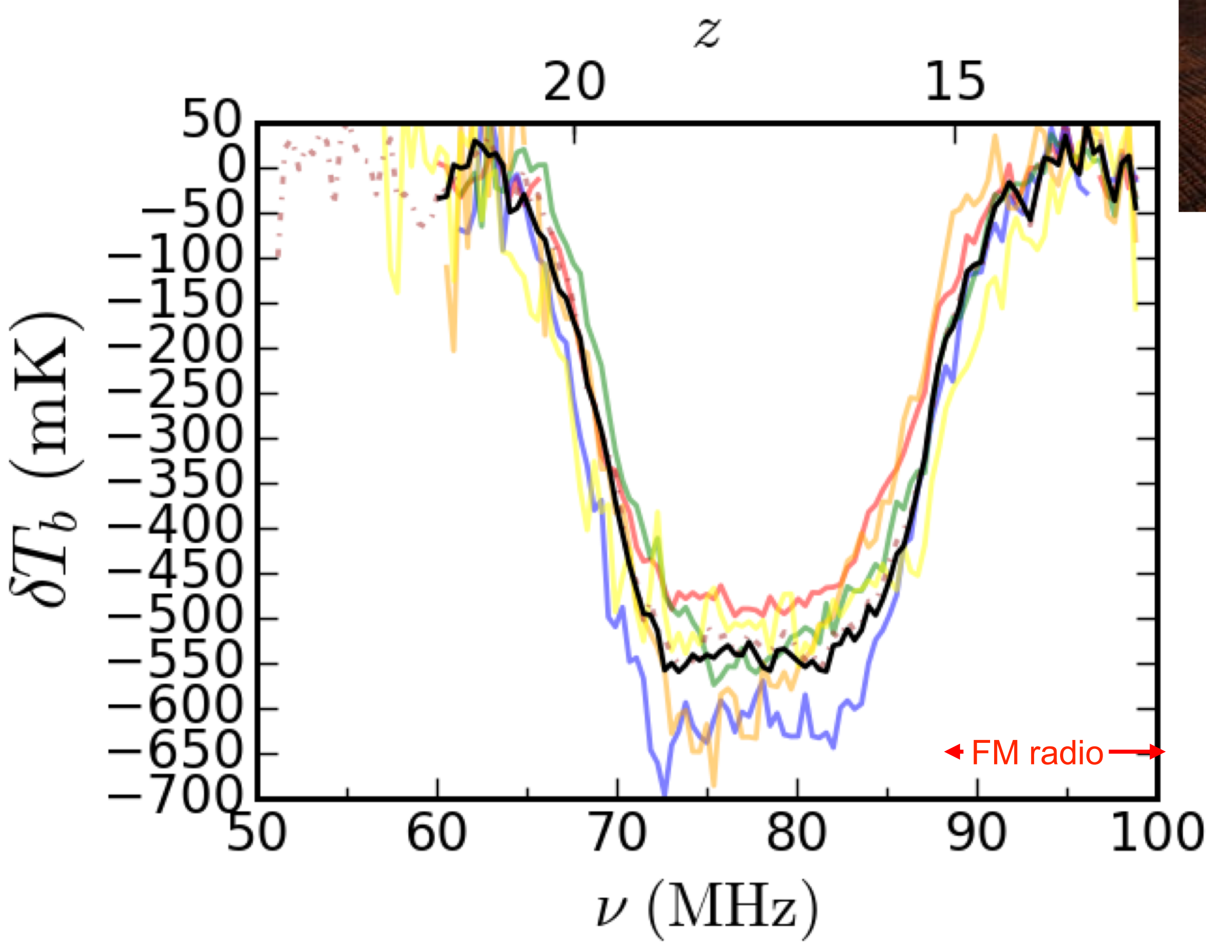
B: Cosmic Dawn: First stars ignite

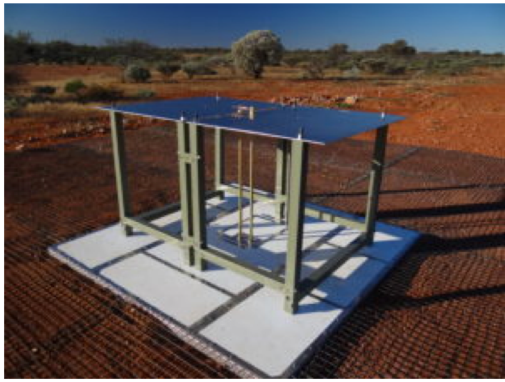
C: Black hole accretion begins



EDGES: Key Features

Bowman et al. 2018, Nature, 555, 67
& next talk by Alan Rogers

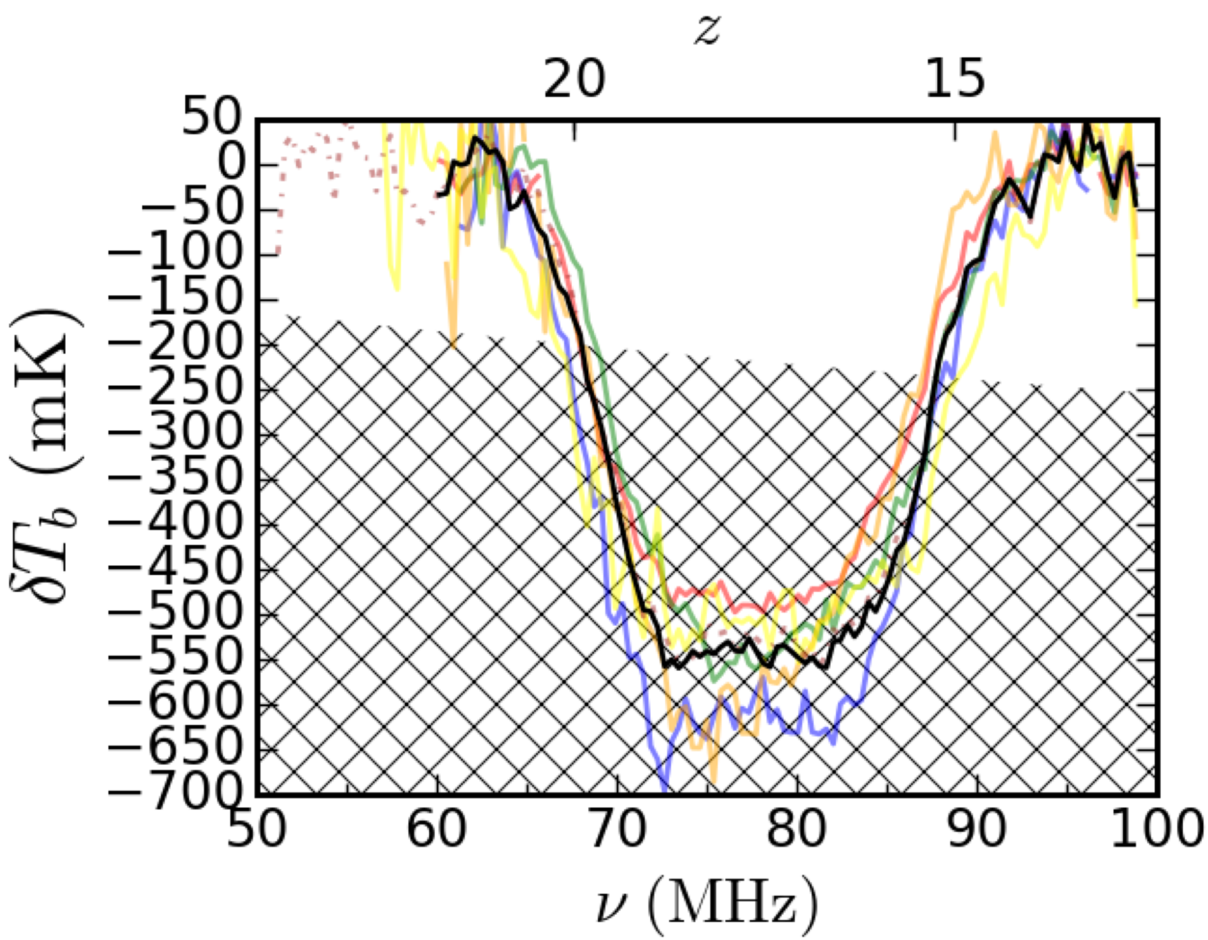




- ionospheric effects

30 MHz

EDGES: Key Features



Requires temperatures colder than those predicted in ~adiabatically cooling of intergalactic medium

Initial Considerations

$$\delta T_b \simeq 27\, \overline{x}_{\mathrm{H\,I}}(1+\delta)\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_{\mathrm{R}}}{T_{\mathrm{S}}}\right)\ \mathrm{mK}$$

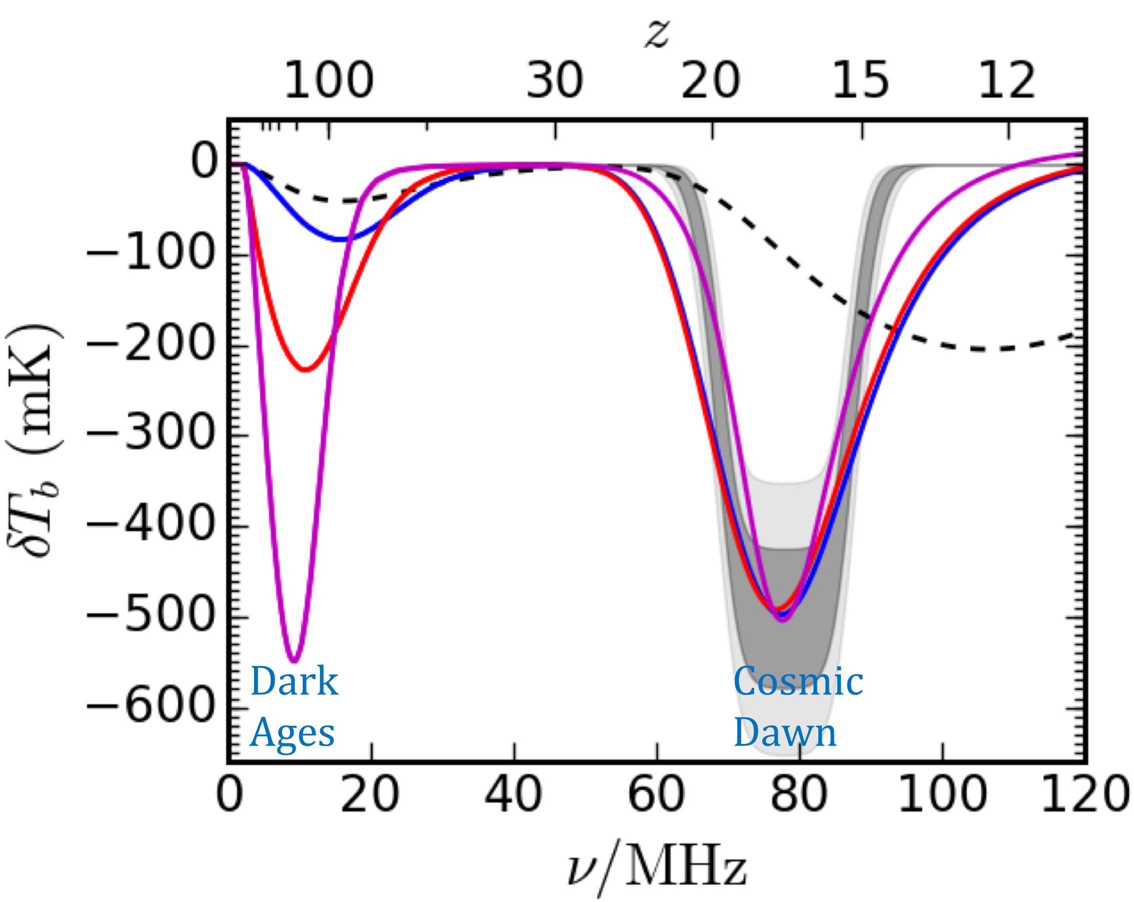
Q. How to amplify signal by a factor of 2-3?

1. Decrease T_S via baryon-Dark Matter interactions.
   - Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slatyer & Wu

2. Increase T_R via Dark Matter decay or synchrotron radiation from black holes, galaxies.
   - Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto

3. Alter the cosmology.
   - McGaugh, Costa et al., Hill et al.

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:

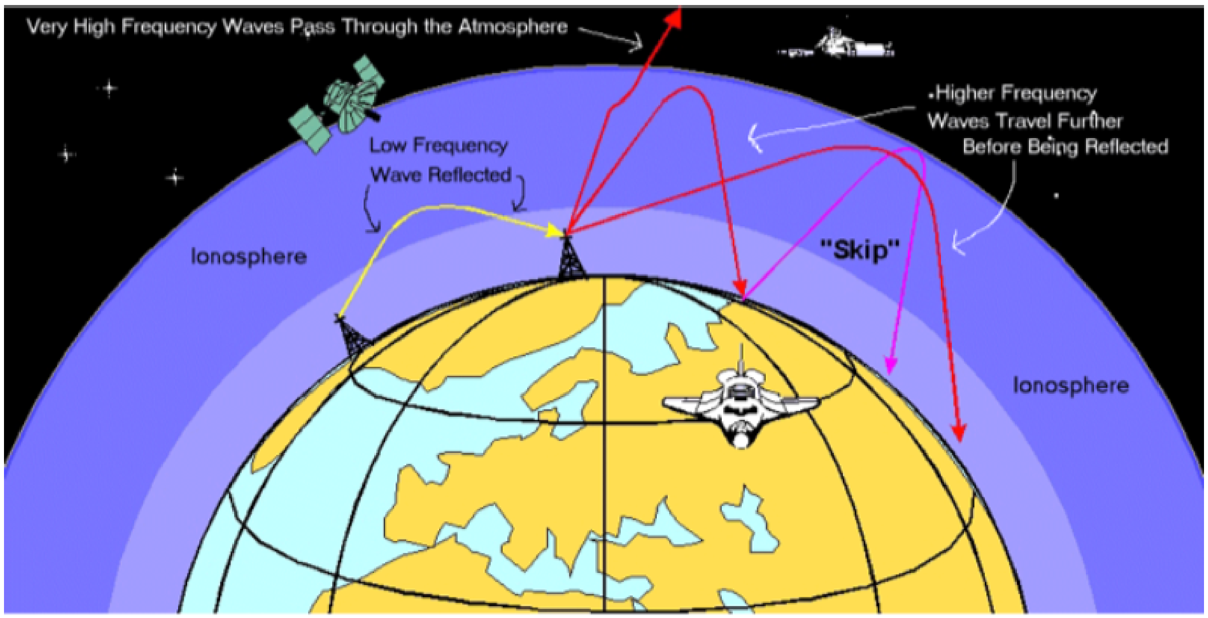
i. Blue curve: Maximum cooling rate is the adiabatic rate, but occurring earlier.

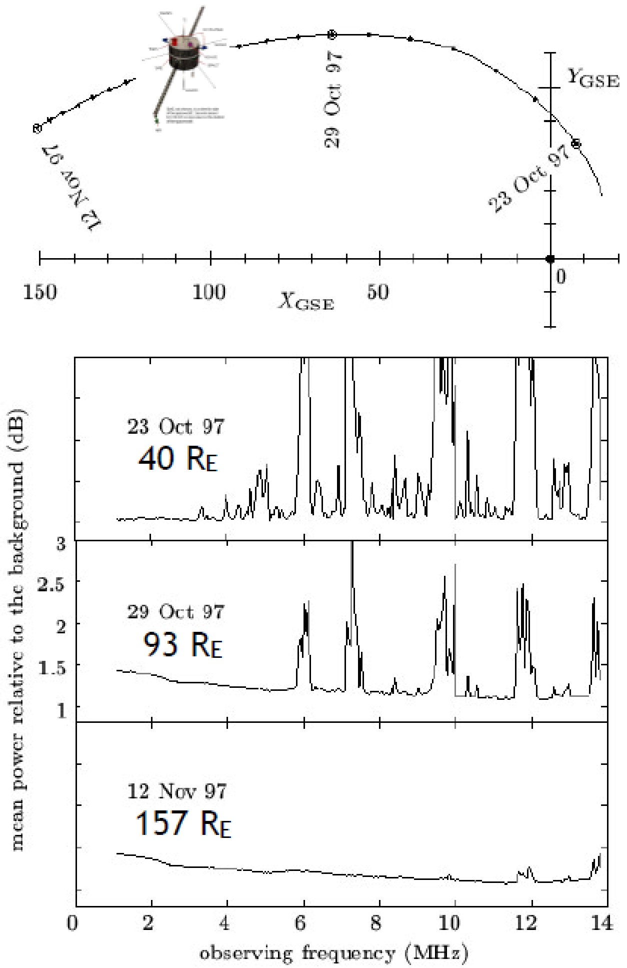
ii. Red curve: Cooling rate both lower and earlier.

iii. Magenta curve: Cooling rate not monotonically declining (i.e. there is a 'preferred epoch' of excess cooling).

Near Earth Radio Environment

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

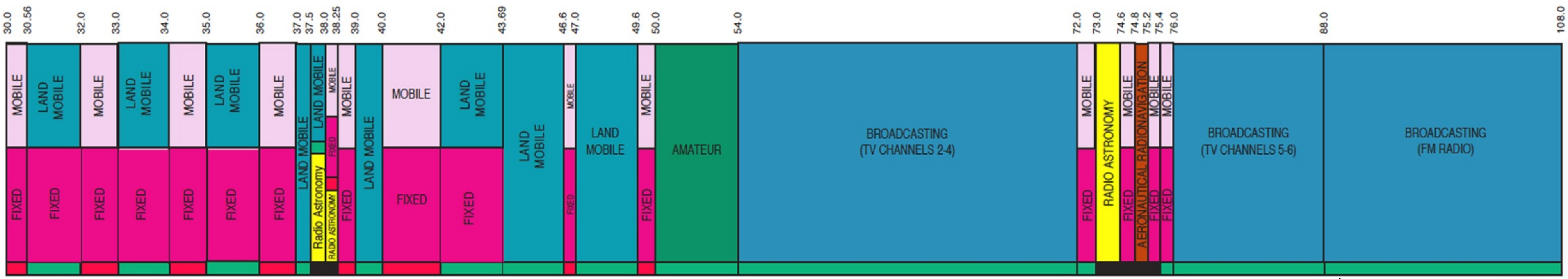




24h averages from Wind/WAVES

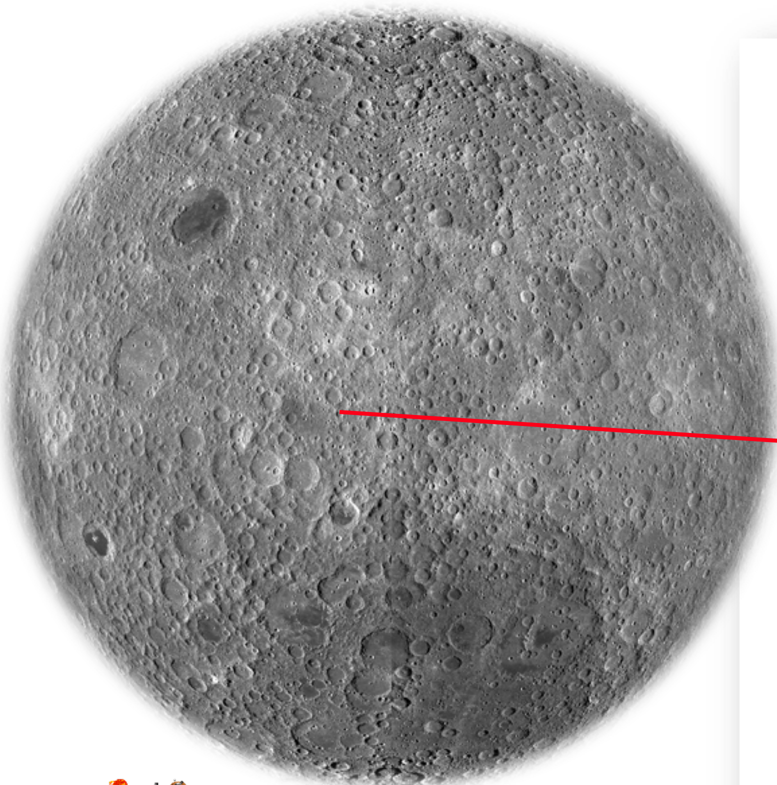
Slide courtesy of C. Cecconi, Observatoire de Paris

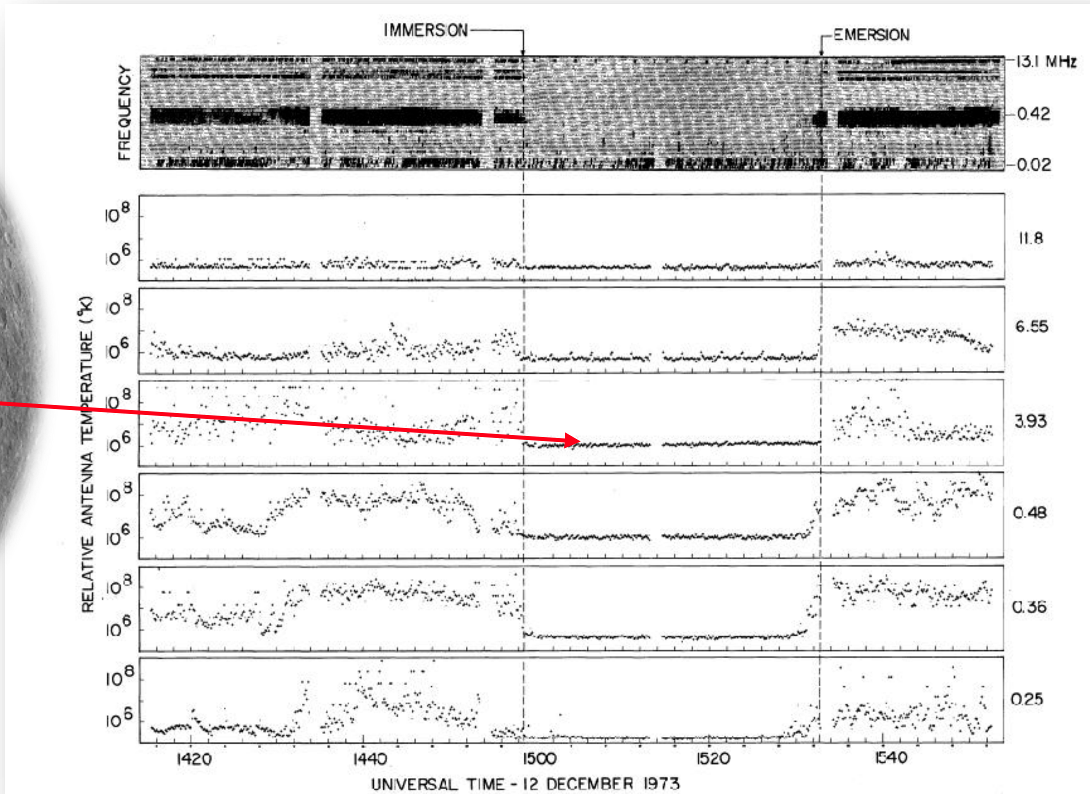
Lunar Farside: No RFI or Ionosphere!



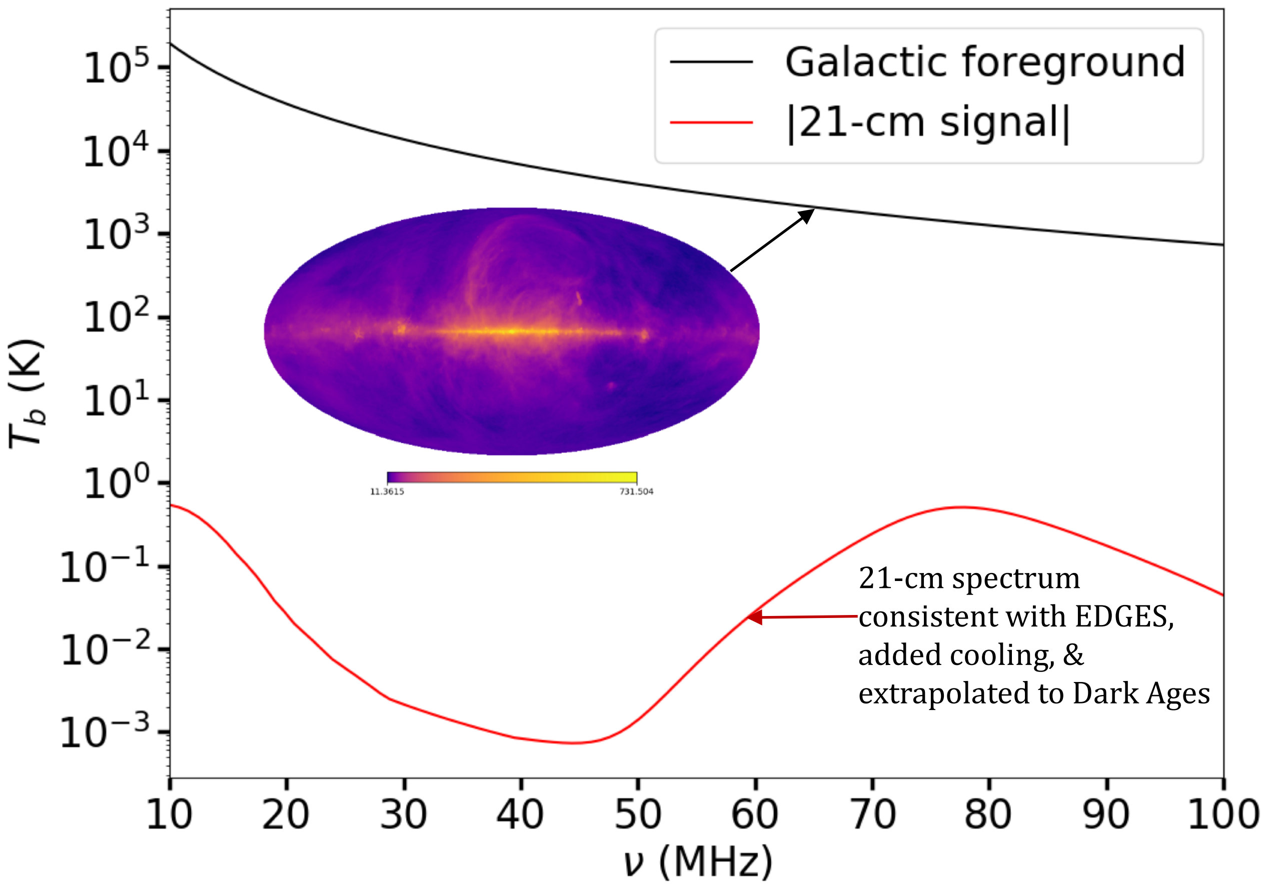
30 MHz **(z=46)** ISM – 40.68 ± .02 MHz **(z=13)** 100 MHz

RAE-2 1973





Why is this a Challenging Observation?



Foreground Characteristics

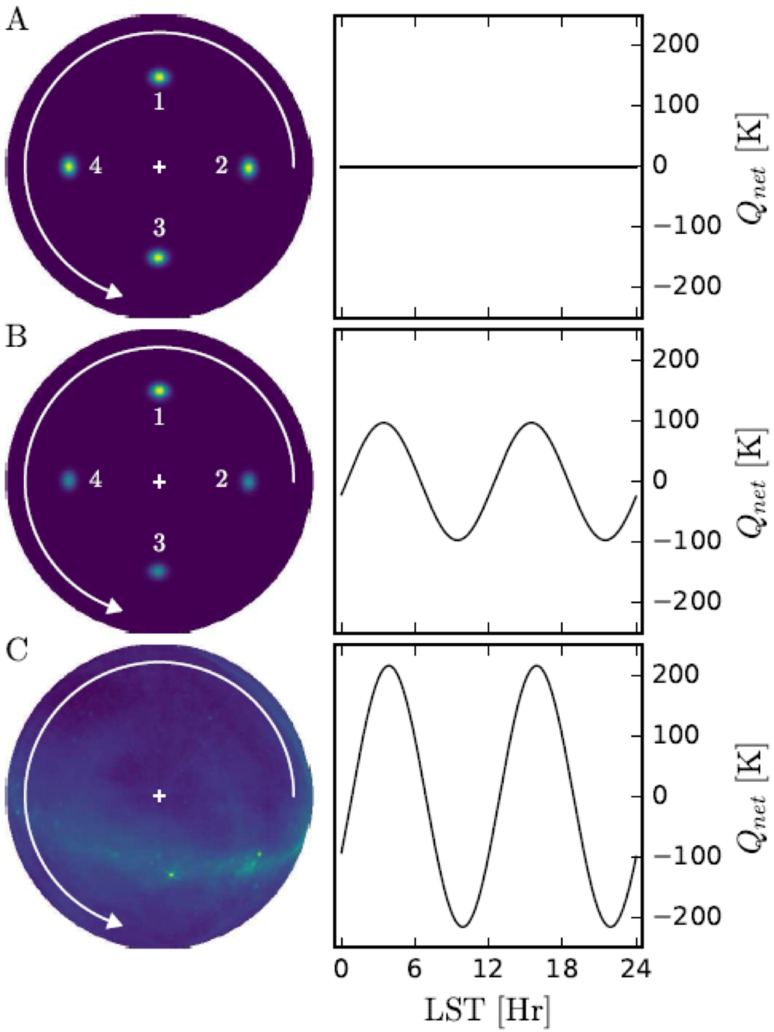
- Spectrally smooth
- Spatial structure
- Polarized

Signal Characteristics

- Spectral structure
- Spatially isotropic
- Unpolarized

How Can Polarimetry Help?

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



Ideal Simulation of the Dynamic & Asymmetric Foreground

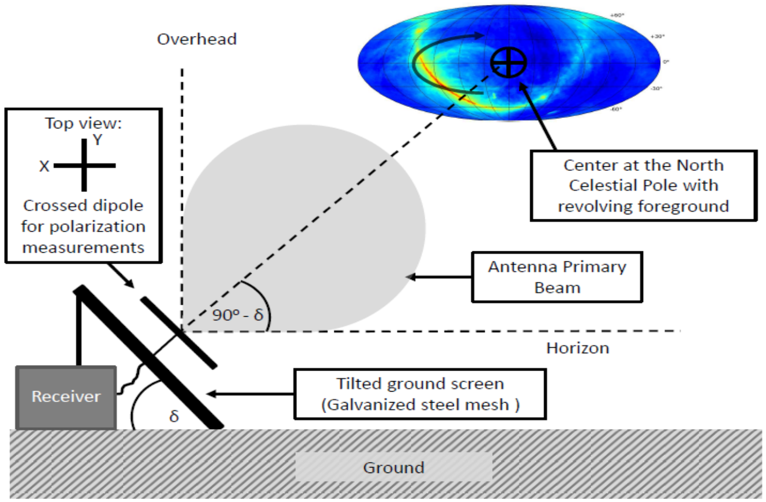
A. *4 symmetric point sources* revolving about pointing center

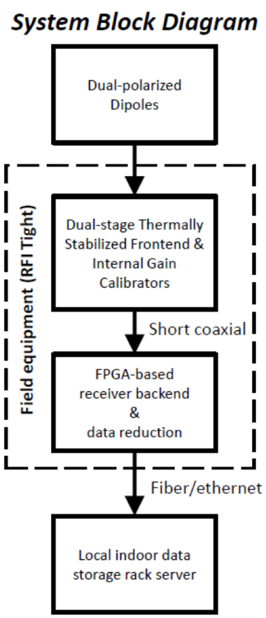
B. *3 weak sources & 1 strong source* revolving

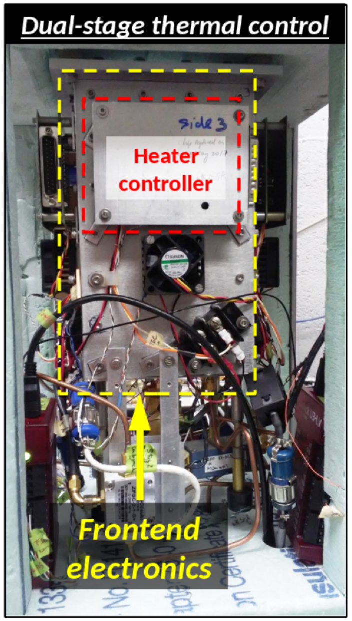
C. *Actual sky map* (Haslam et al. 1982) centered on North Celestial Pole

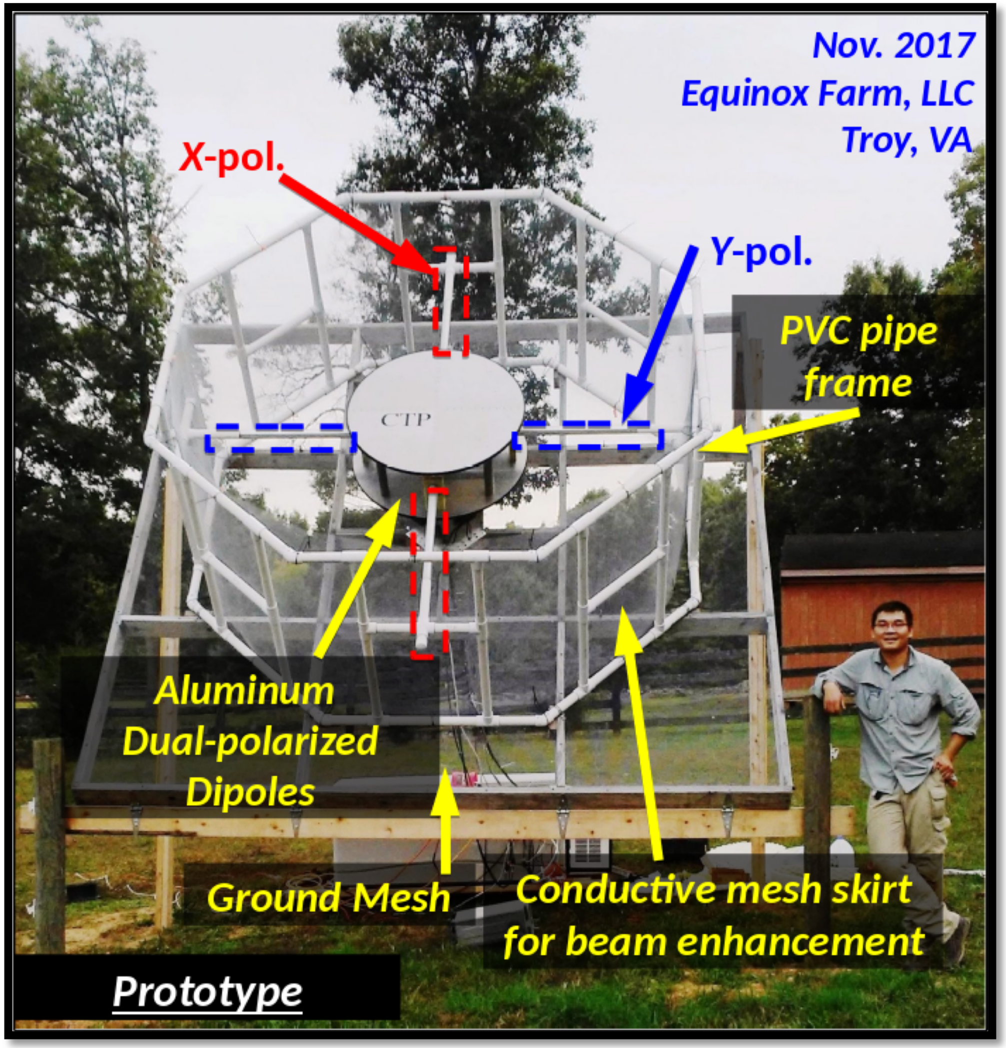
Remember: No net polarization expected from isotropic global 21-cm signal

The Cosmic Twilight Polarimeter (CTP): Dynamic Polarimetry Testbed







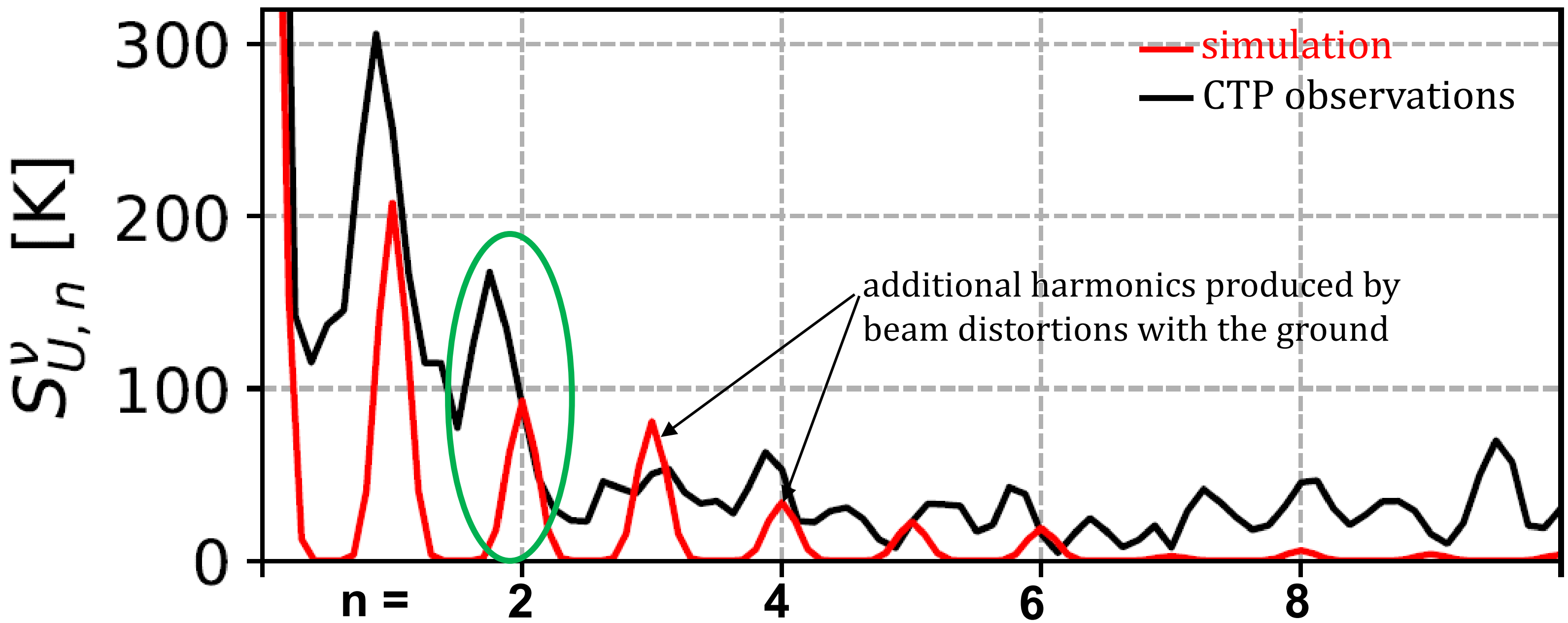


Operates over 60-80 MHz

Nhan, Bradley, & Burns, 2018

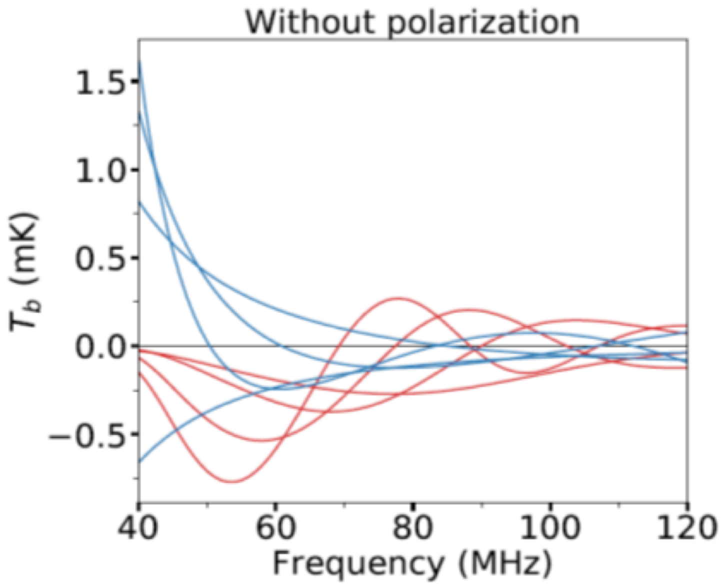
Initial Results from the Cosmic Twilight Polarimeter

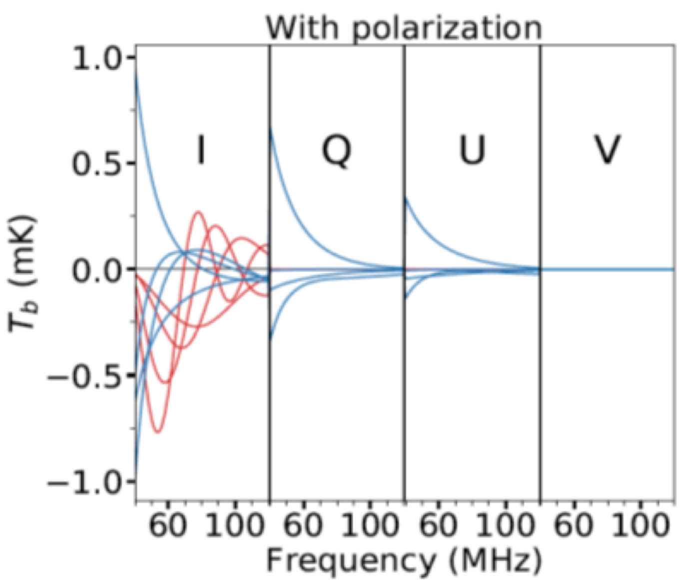
Nhan, B., 2018, Ph.D. dissertation, U. Colorado



- 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?

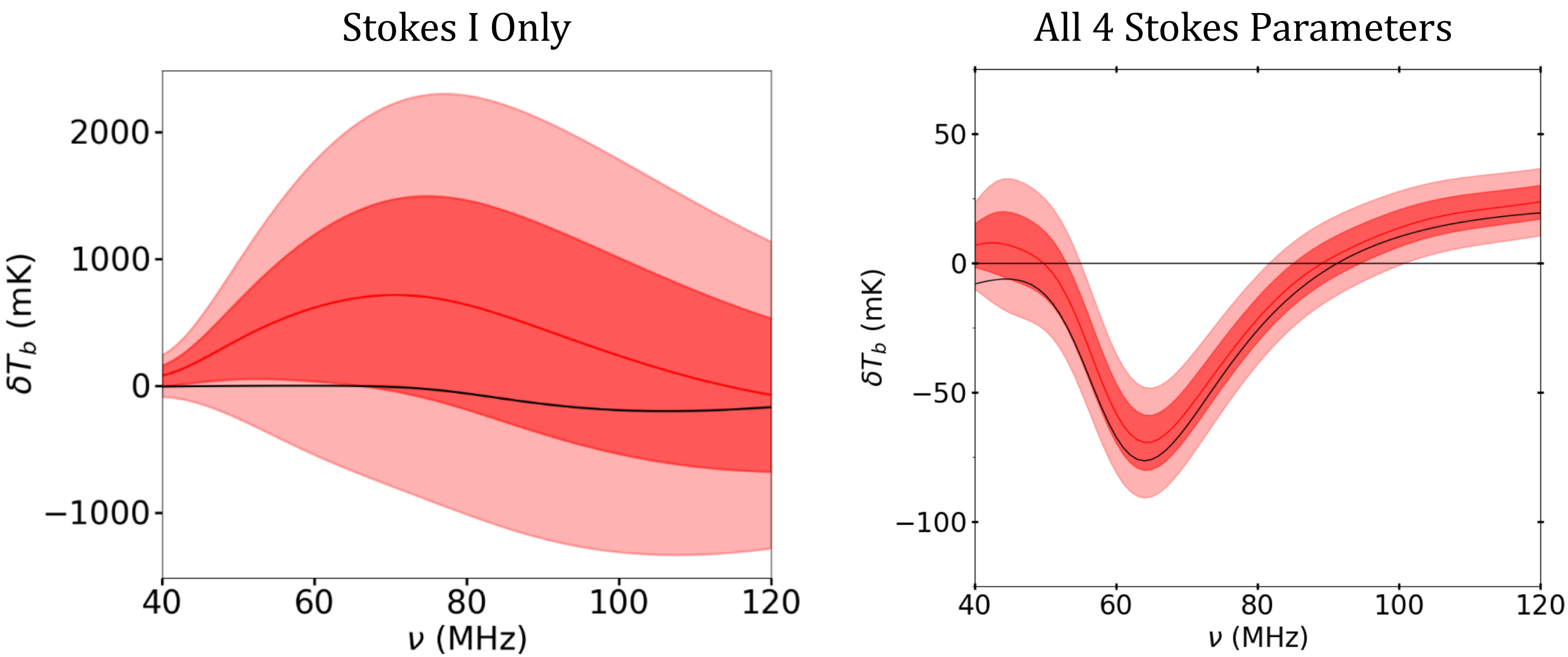




Employ Pattern Recognition Techniques:

- 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)

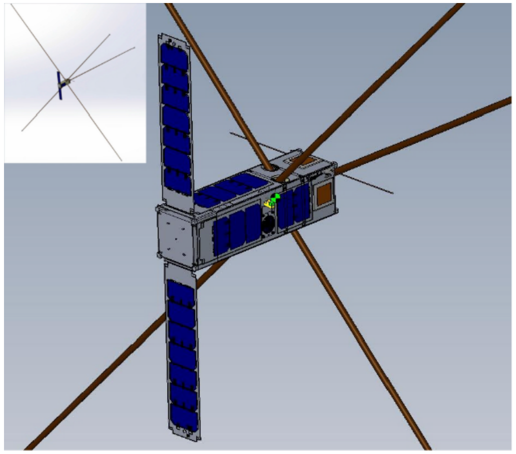
How much difference does polarization data make?

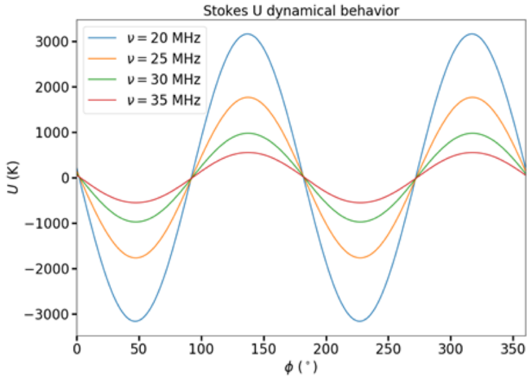


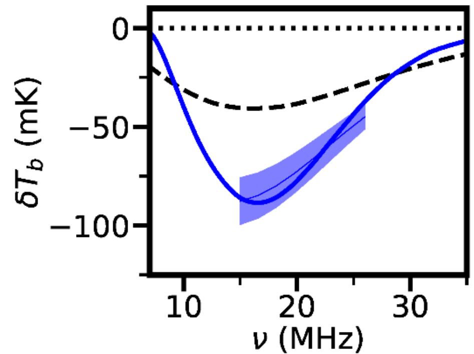
- **Burns et al.** 2017, *A Space-based Observational Strategy for Characterizing the First Stars and Galaxies Using the Redshifted 21cm Global Spectrum*, ApJ, 844, 33.
- **Tauscher, K., Rapetti, D., Burns, J., Switzer, E.** 2018, *Global 21-cm Signal Extraction from Foreground & Instrumental Effects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

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

- DAPPER will be placed in proximity to NASA's Lunar Gateway to reduce Earth-based RFI.
- Operates over bandwidth of 15-30 MHz (93≥z≥46).
- Dual orthogonal ≈ 7-m tip-to-tip 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

- The redshifted 21-cm Global Spectrum at ≲30 MHz offers the prospect of probing the nature & character of Dark Matter in the Dark Ages.
- These observations need to be conducted in space, in orbit of the Moon, to eliminate Earth ionospheric & RFI effects.
- Dynamic polarization provides an independent measure of the galactic foreground.
- 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.
- We are developing a SmallSat mission concept (DAPPER) to utilize both polarimetry and pattern recognition to detect deviations from the standard cosmology model.