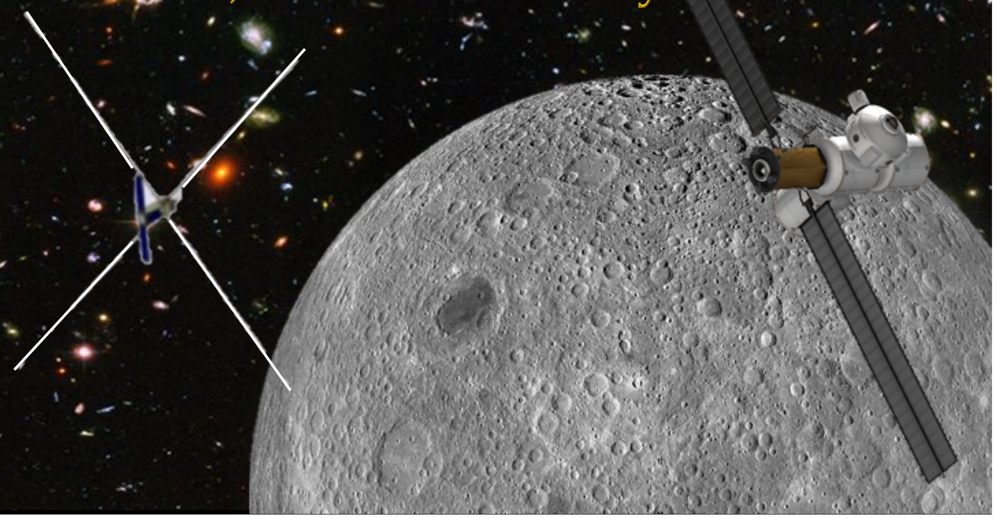
NESS
Network for Exploration and Space Science
A NASA-funded SSERVI Team

Dark Cosmology: Investigations of Dark Matter with the Dark Ages Polarimeter PathfindER (DAPPER)

Jack Burns[1], Stuart Bale[2], Richard Bradley[3], Keith Tauscher[1], David Rapetti[1,4], Jordan Mirocha[5]

[1]University of Colorado Boulder, [2]UC-Berkeley, [3]NRAO, [4]NASA Ames Research Center, [5]McGill University



URSI National Radio Science Meeting: *Cosmology & Astrophysics at Low Frequencies*

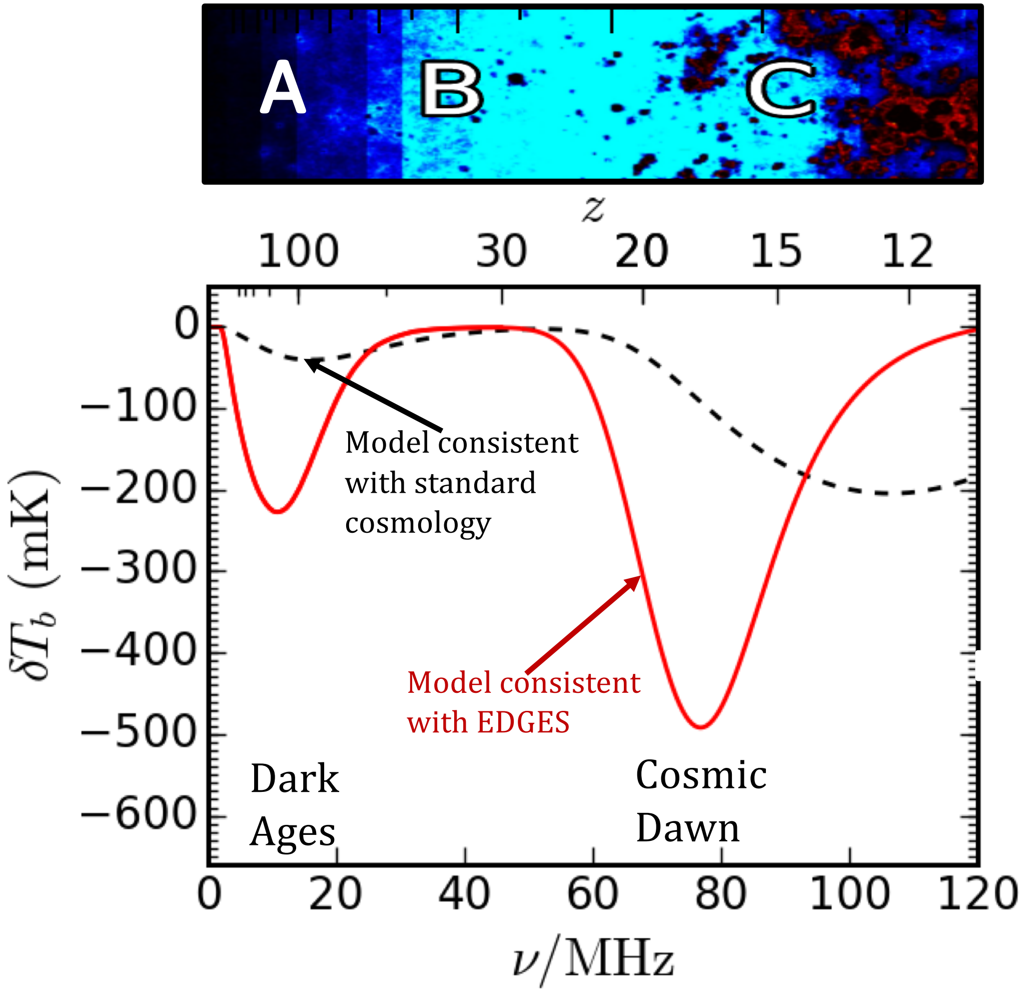
What is the 21-cm Global signal?

Spectral Features:

A: Dark Ages: test of standard cosmological model

B: Cosmic Dawn: First stars ignite

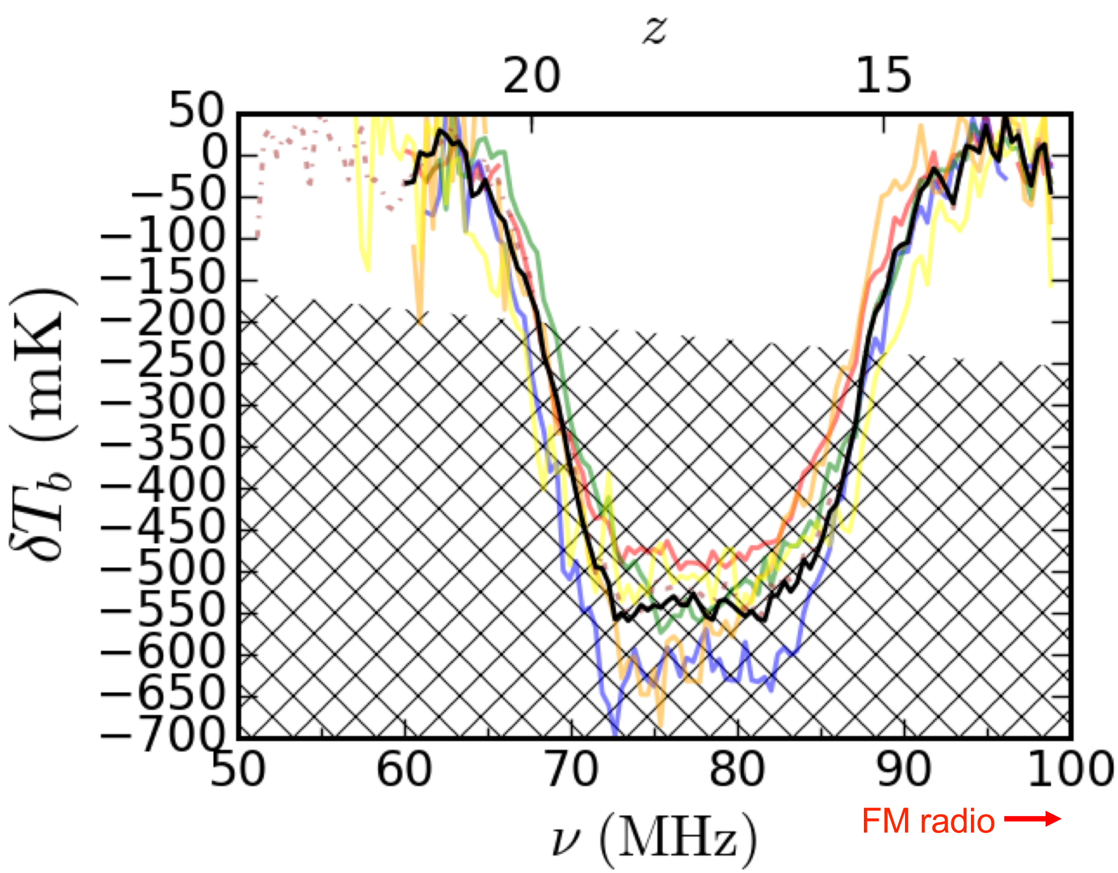
C: Black hole accretion begins



EDGES: Key Features

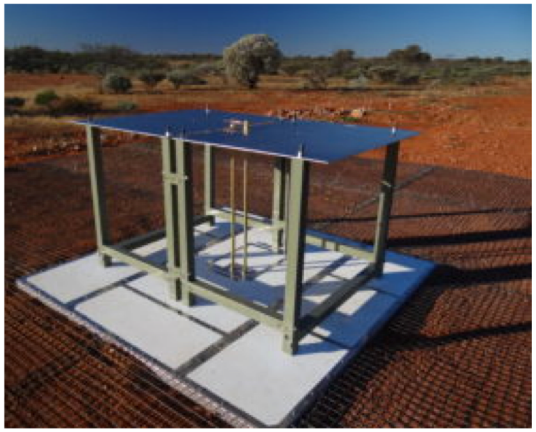
Bowman et al. 2018, Nature, 555, 67

ionospheric effects



30 MHz

FM radio →



Initial Considerations

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

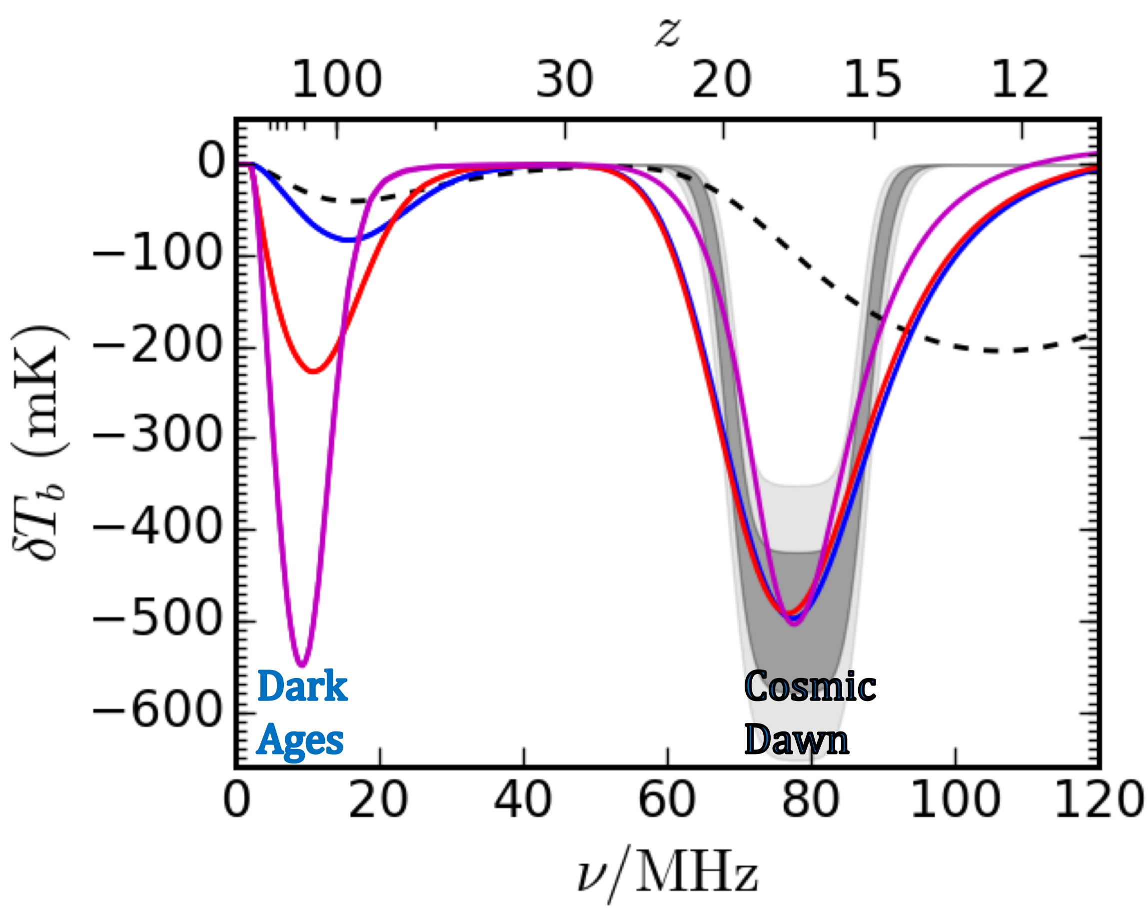
Q. How to amplify signal by a factor of 2-3?

1. 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

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

3. Decrease T_S via baryon-Dark Matter interactions which cools the hydrogen.
   - Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slatyer & Wu

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:

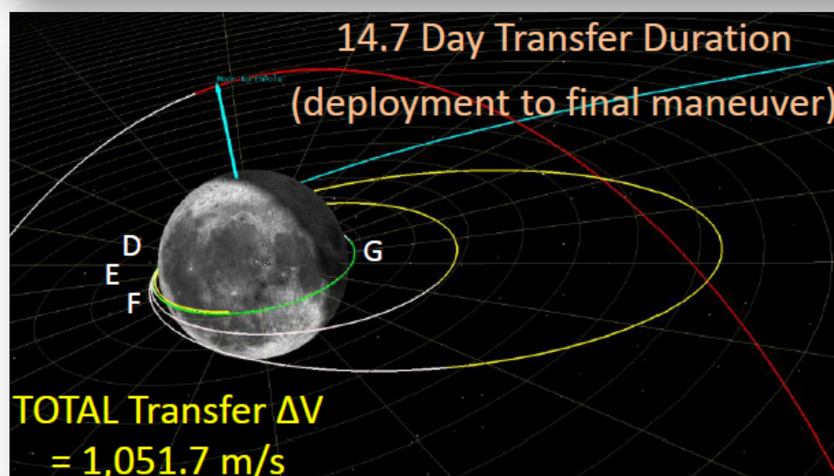
i. Blue curve: Maximum cooling rate is the adiabatic rate, but occurring earlier.

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

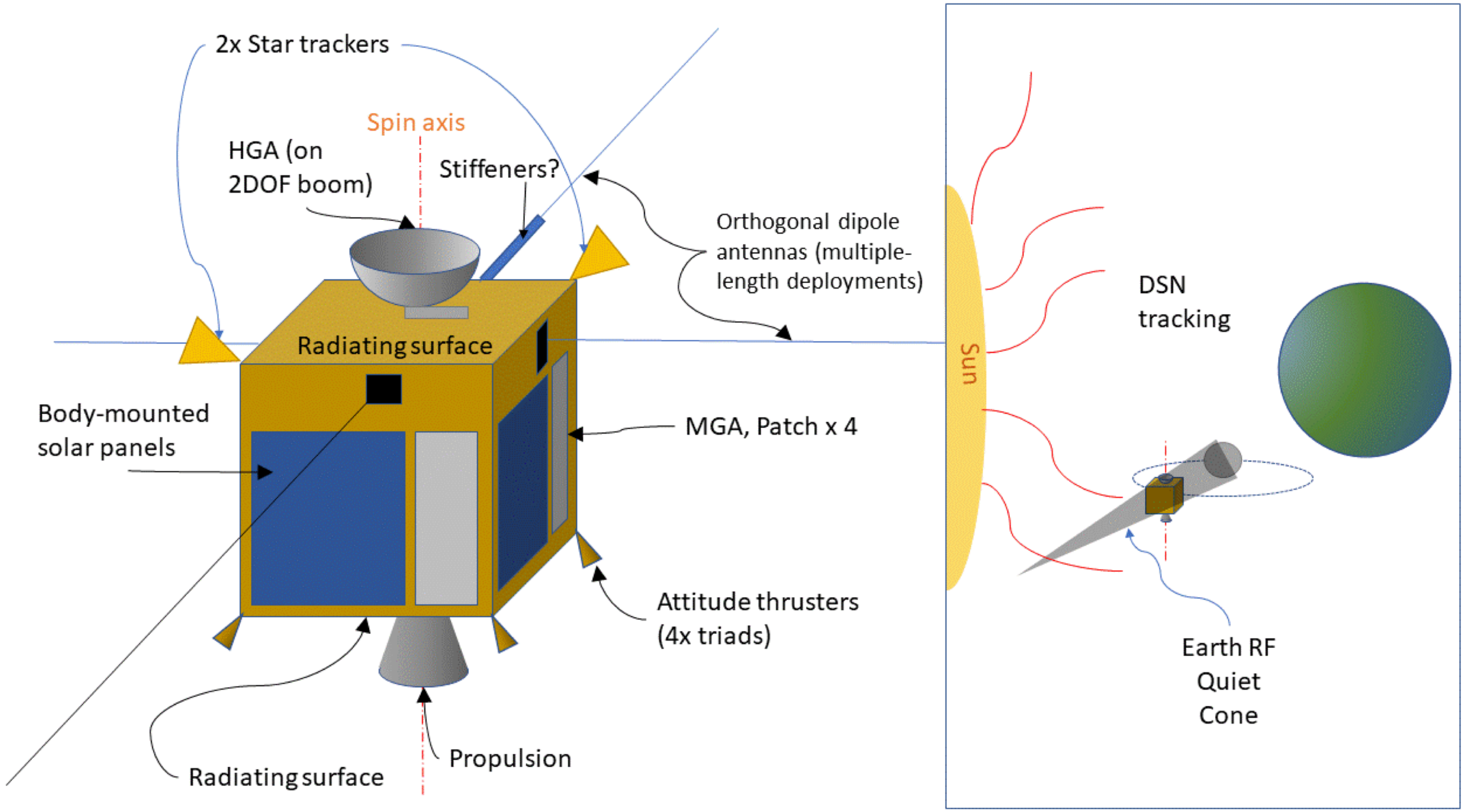
iii. Magenta curve: Cooling rate not monotonically declining (i.e. there is a ‘preferred epoch’ of excess cooling).

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

- **Science Objectives:**
  - Search for deviations from the standard cosmological model & impact of exotic physics
  - Verify EDGES results
- DAPPER will launch from NASA's Lunar Gateway & transfer to a 50×125 km low lunar orbit
- Operates over primary bandwidth of 17-30 MHz (83 ≥z≥46) and sparse secondary sampling from 30-100 MHz (46 ≥z≥13)
- Bandwidth determined by antenna resonances from 3 length deployments of thin-wire, spinning, dual orthogonal dipole antennas (TRL=8) ranging from 4.4-7.6 m tip-to-tip
- Low noise amplifiers & dual channel receiver to measure all 4 Stokes parameters. Based upon FIELDS instrument currently flying on Parker Solar Probe (TRL = 8)
- Projection-induced polarimetry used to independently constrain foreground



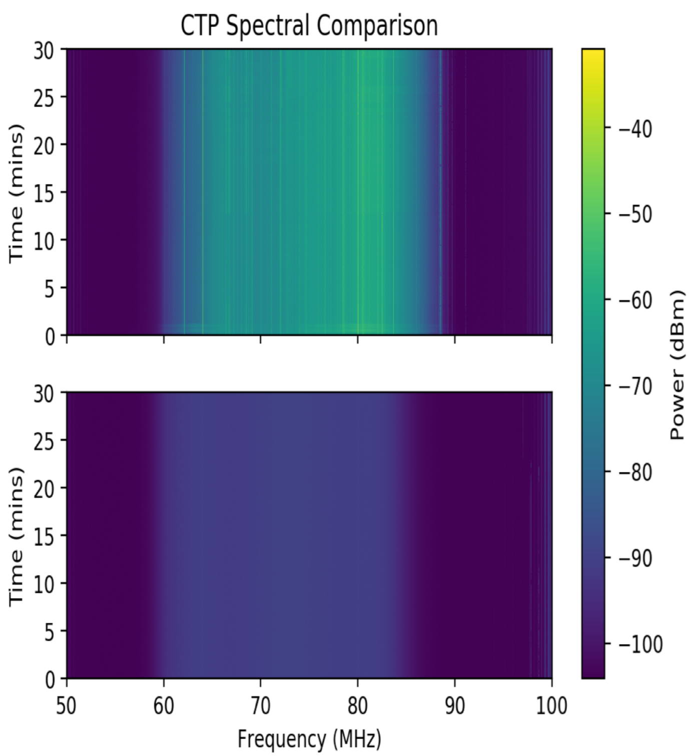
The Dark Ages Polarimeter PathfindER (DAPPER)

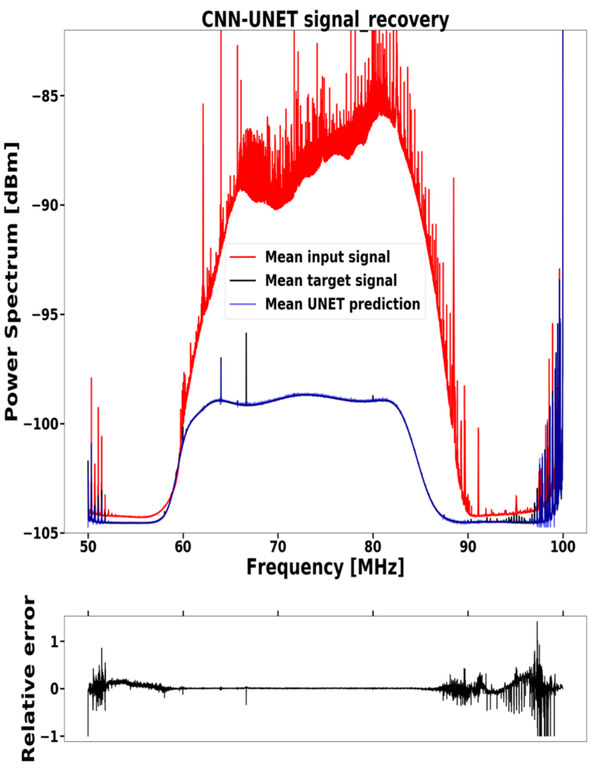


DAPPER: Internal RFI Mitigation Strategy

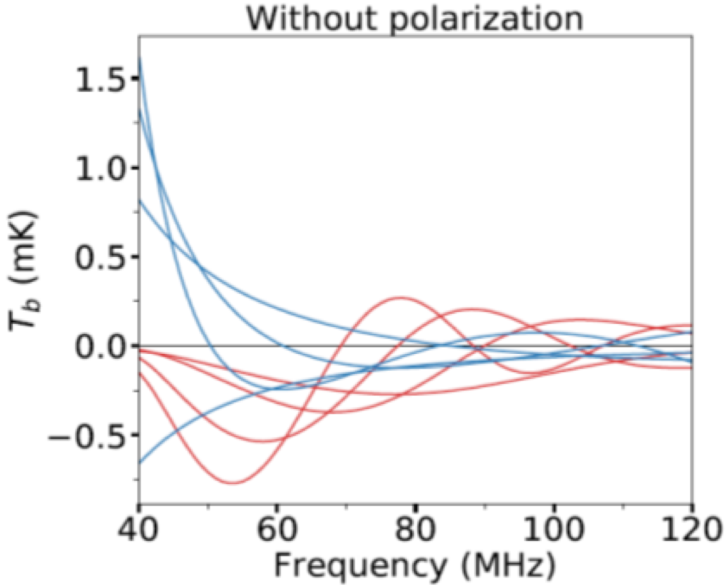
- Active Control
  - Faraday Cage + Polyphase Filters
  - Crystal Oscillator Masking of Internal RFI

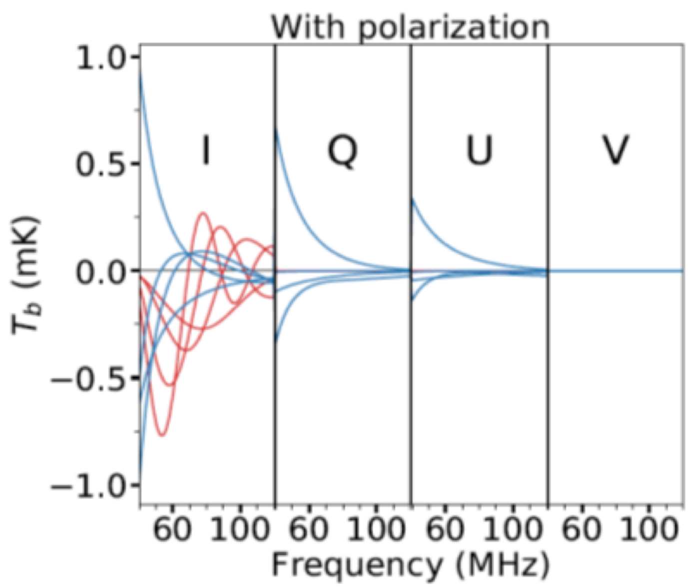
- Knowledge-Based Measurement of RFI
  - Frequency-Tone injection system to accurately measure gain variations
  - Neural Network Separation of RFI from Sky + 21-cm spectrum





How can we extract the 21-cm signal?





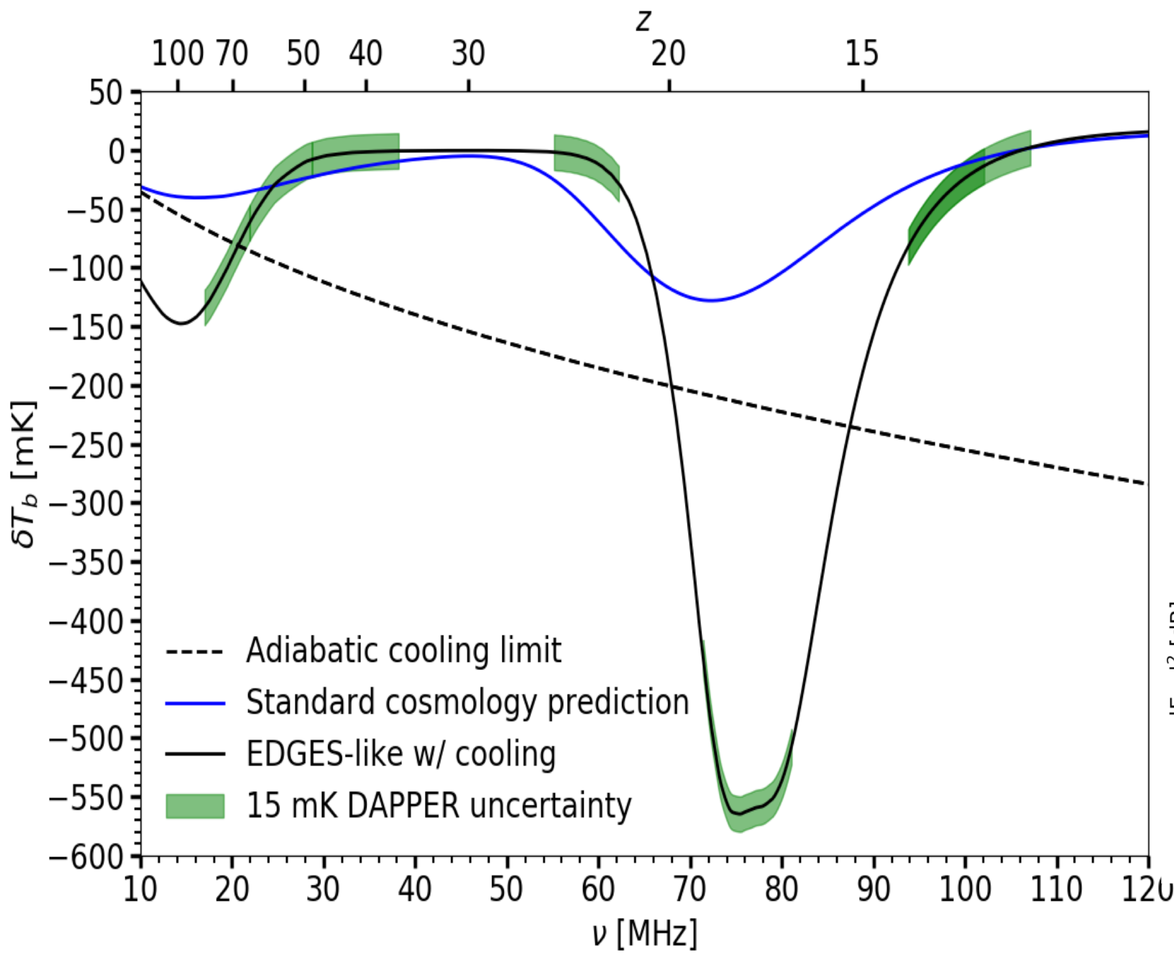
Employ Pattern Recognition + Dynamic Polarimetry Techniques:

- 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)

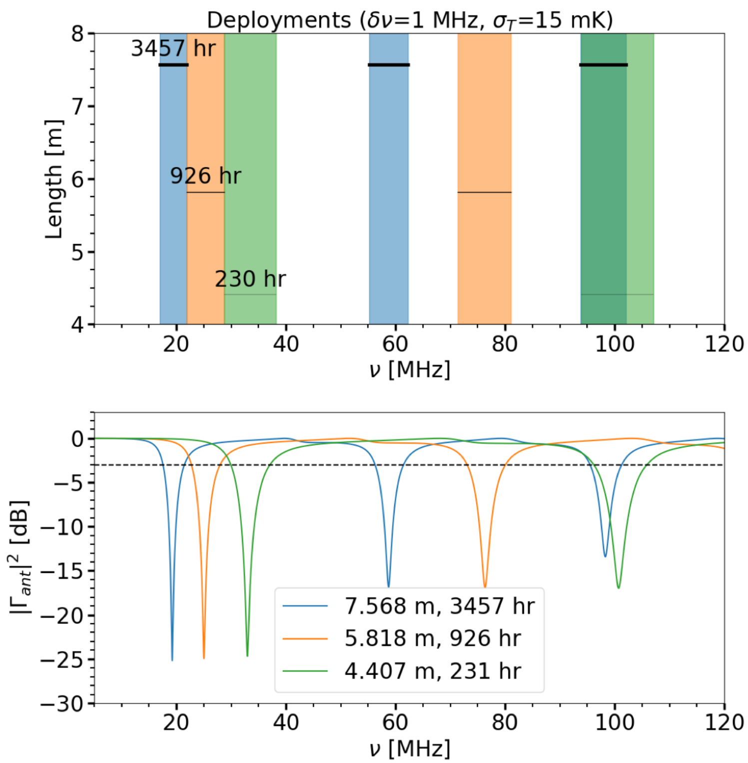
See also talks by:

- Rapetti+, *Full Data Analysis Pipeline*, J4-15, 11:40
- Tauscher+, *Challenges of Global EoR Detection*, J5-3, 13:45
- Bordenave+, *The Cosmic Twilight Polarimeter,* J5-9, 15:30

What is the expected DAPPER Performance?



DAPPER Bandpasses



DAPPER will measure amplitude of 21-cm spectrum to the level required to distinguish (at >5σ) the standard cosmological model from that of additional cooling derived from current EDGES results

Team Members & Recent Publications

Team Member	Expertise & Experience	Role
J. O. Burns, U. Colorado	cm, meter-wave observations; CTP; data processing; cosmology simulations	PI. Ensures mission success, mission reporting; data analysis
S. D. Bale, UC Berkeley	P.I. for Parker Solar Probe FIELDS and STEREO/WAVES; meter-wave instrumentation	Co-I. Instrument scientist
R. Bradley, NRAO	Meter-wave instrumentation; CTP; PAPER; HERA	Co-I. Polarimeter; receiver
NASA Ames Research Center	Extensive lunar mission experience including LADEE and LCROSS	Mission Design; management, Navigation
J. Bowman, ASU	Meter-wave instruments; P.I. EDGES; HERA	Collaborator; RF instrument
H. Falcke, Radbound U.	Meter-wave instrumentation; NCLE lunar radio experiment	Collaborator; RFI environment
S. Furlanetto, UCLA	21-cm cosmology theory	Collaborator; modeling of DAPPER spectrum
M. Klein- Wolt, Radbound U.	Meter-wave instrumentation; NCLE lunar radio experiment	Collaborator; RFI environment
R. MacDowall, GSFC	Meter-wave space instruments; Solar Probe, STEREO, WIND	Collaborator; RFI environment; RF instrument
J. Mirocha, McGill U.	21-cm cosmology theory	Collaborator; modeling of DAPPER spectrum
B. Nhan, U. Virginia	Meter-wave instrumentation; CTP	Collaborator; polarimeter
D. Rapetti, U. Colorado	Signal extraction & modelling	Postdoc; data analysis pipeline
K. Tauscher, U. Colorado	Signal extraction & modelling	Graduate student; data analysis

- **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.
- **Tauscher, K., Rapetti, D., Burns, J.** 2018, *A new goodness-of-fit statistic and its application to 21-cm cosmology,* Journal of Cosmology and Astroparticle Physics, Issue 12, article id. 015.
- **Nhan, B., Bordenave, D., Bradley, R., Burns, J., Klima, P., Tauscher, K., Rapetti, D.** 2019, *A Proof of Concept Experiment to Constrain the Foreground Spectrum for Global 21 cm Cosmology Through Projection-Induced Polarimetry,* submitted to ApJ., arXiv:1811.04917.

Summary and Conclusions

- The redshifted 21-cm Global Spectrum at $\lesssim$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.
- Projection-induced 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.