Detecting the First Galaxies with the Global 21-cm Signal: The Dark Ages Radio Explorer

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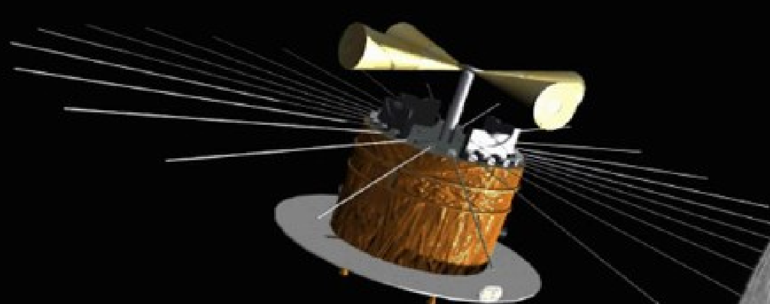

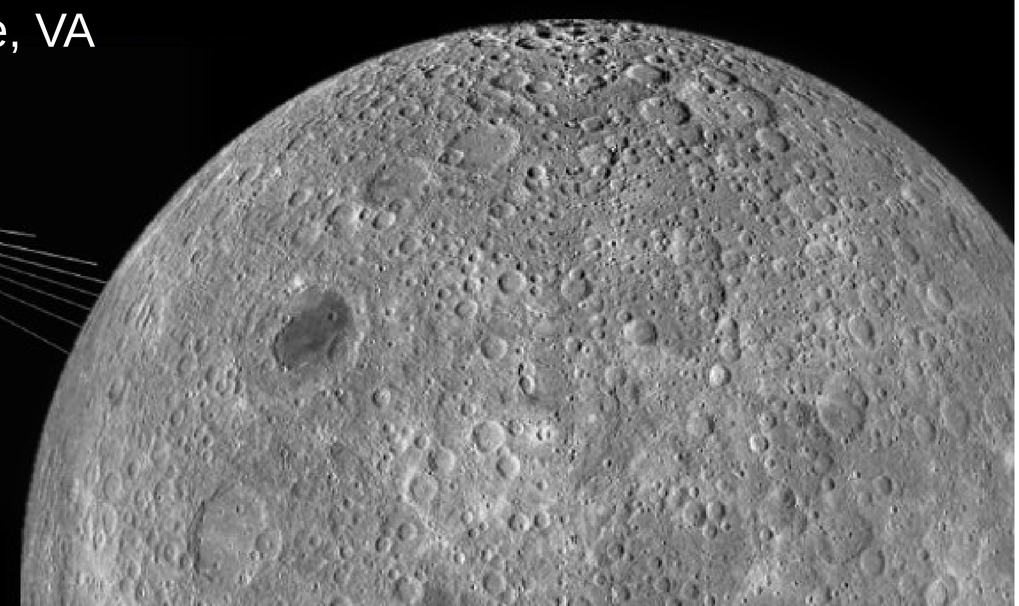

Radio Futures II
August 4, 2016

DARE Project Team

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Observatory Project Management: Ball Aerospace & Technologies Corp.: W. Purcell & D. Newell

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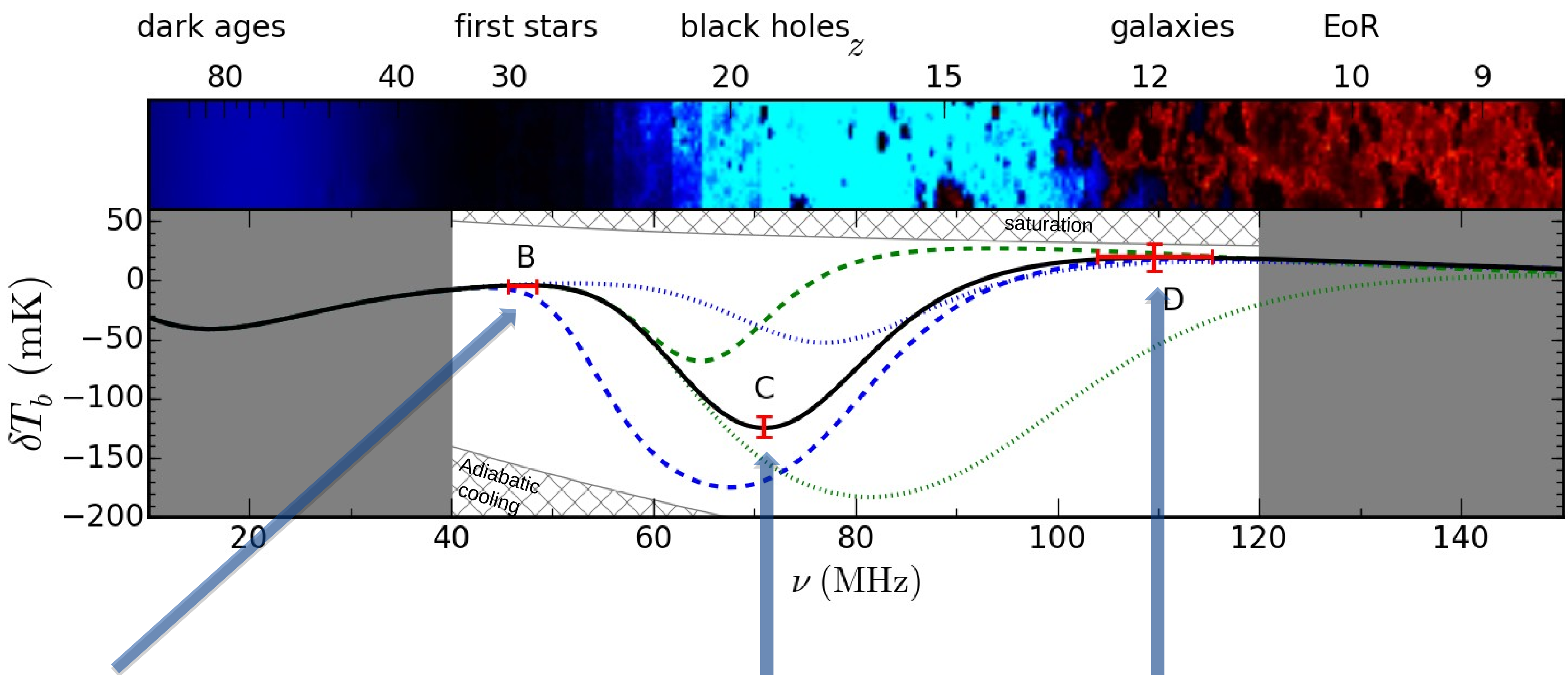
The Science

The 21-cm Global Signal Reveals the Birth & Characteristics of the First Stars & Galaxies



B: ignition of first stars

- When did the First Stars ignite? What were these First Stars?
- What surprises emerged from the Dark Ages?

C: heating by first black holes

- When did the first accreting black holes turn on? What was the characteristic mass?

D: the onset of reionization

- When did Reionization begin?

--- · · · uncertainties in 1st star models

--- · · · uncertainties in 1st black hole models

DARE
DARK AGES RADIO EXPLORER

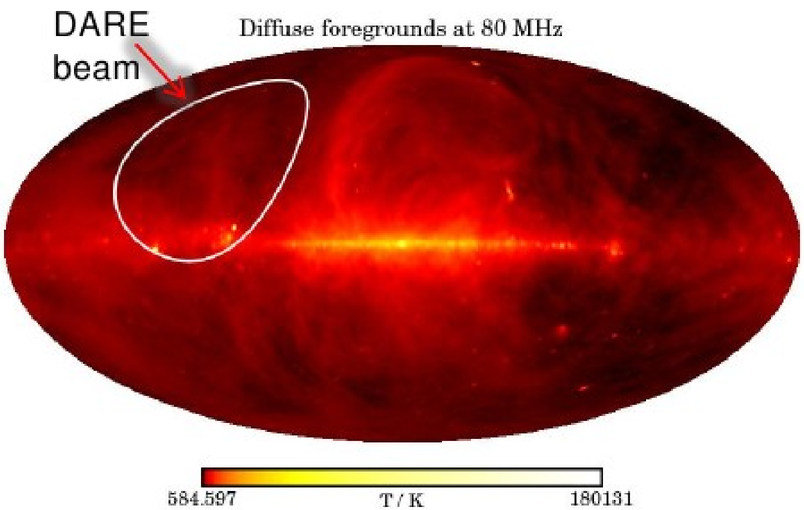
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006 and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

Foregrounds: Major Challenge

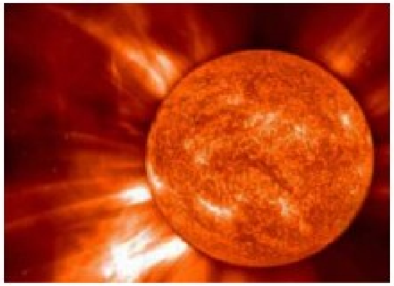
- **Earth's Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as ν^{-2} so they get much worse quickly below ~100 MHz.
- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO (10^8 K) or lunar nearside (10^6 K), RFI brightness T_B is high.
- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial, $\log T_{\rm fg} = \sum_{i=0}^{N_{\rm poly}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).
  - EDGES finds spectral structure at levels <8 mK in foreground at 100-200 MHz.
- **Other Foregrounds -** lunar thermal emission & reflections; Jupiter; Recombination lines.

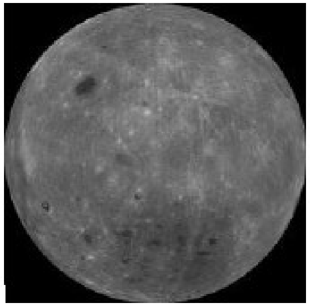
Extraterrestrial Foregrounds

1) Milky Way synchrotron emission + "sea" of extragalactic sources.

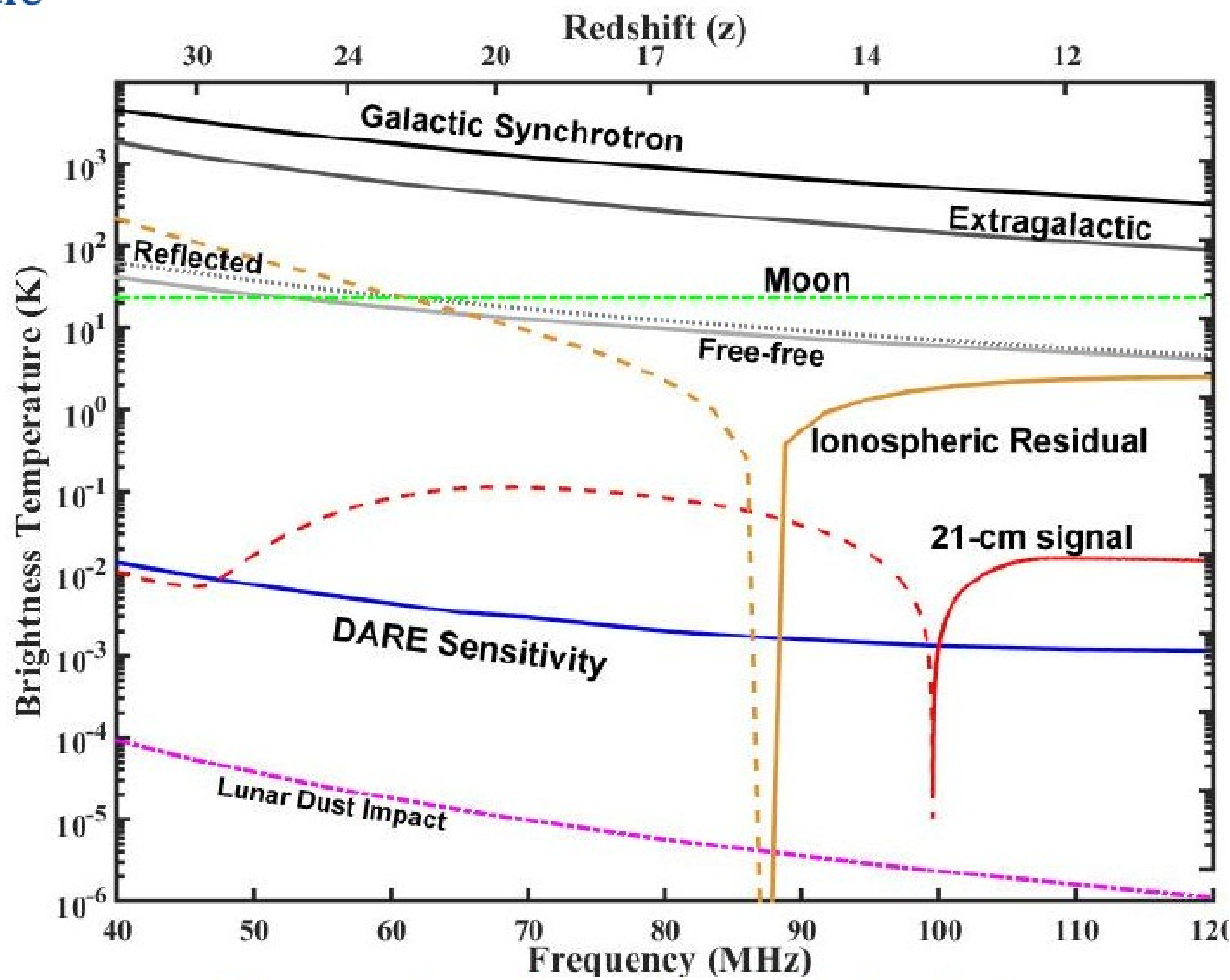


2) Solar system objects: Sun, Jupiter, Moon.





Spectra of Foregrounds



=>Must employ advanced statistical techniques to simultaneously fit signal, foregrounds, & instrument parameters

Observational Approaches for Detection of Global 21-cm Monopole

Single Antenna Radiometers

- EDGES (Bowman & Rogers)
- SARAS (Patra et al.)
- LEDA (Greenhill, Bernardi et al.)
- SCI-HI (Peterson, Voytek et al.)
- BIGHORNS (Sokolowski et al.)
- DARE (Burns et al.)

Challenges include systematics arising from stability issues, accurate calibration, polarization leakage, foregrounds.

Small, Compact Interferometric Arrays

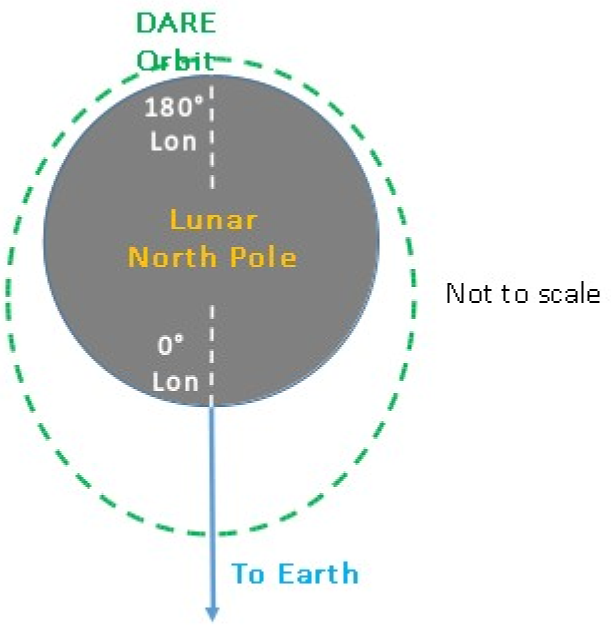
- Vadantham et al.
- Mahesh et al.
- Presley, Parsons & Liu
- Subrahmanyan, Singh et al.

Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.

The Mission

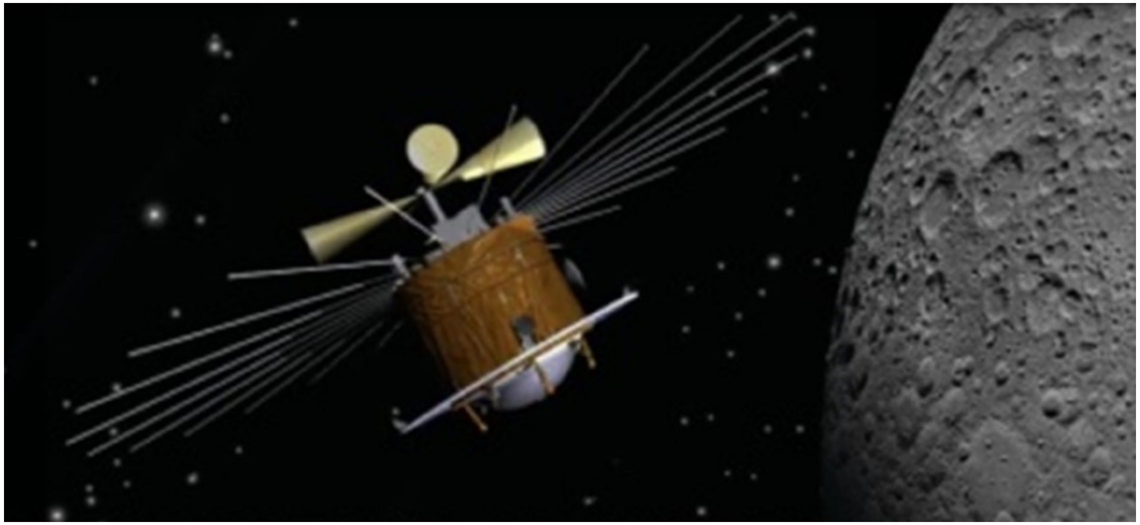
The Purpose

- Place a radiometer in orbit about the Moon
- Eliminate the ionosphere as a source of error
- Use the Moon to shield the radiometer from Earth RFI and solar radiation



The Spacecraft and Mission

- NASA Midscale Explorer
- Launch September 2023
- 2.2 Year Duration
- Cost Cap: $250M



Signal Extraction Methodologies

Pattern Matching

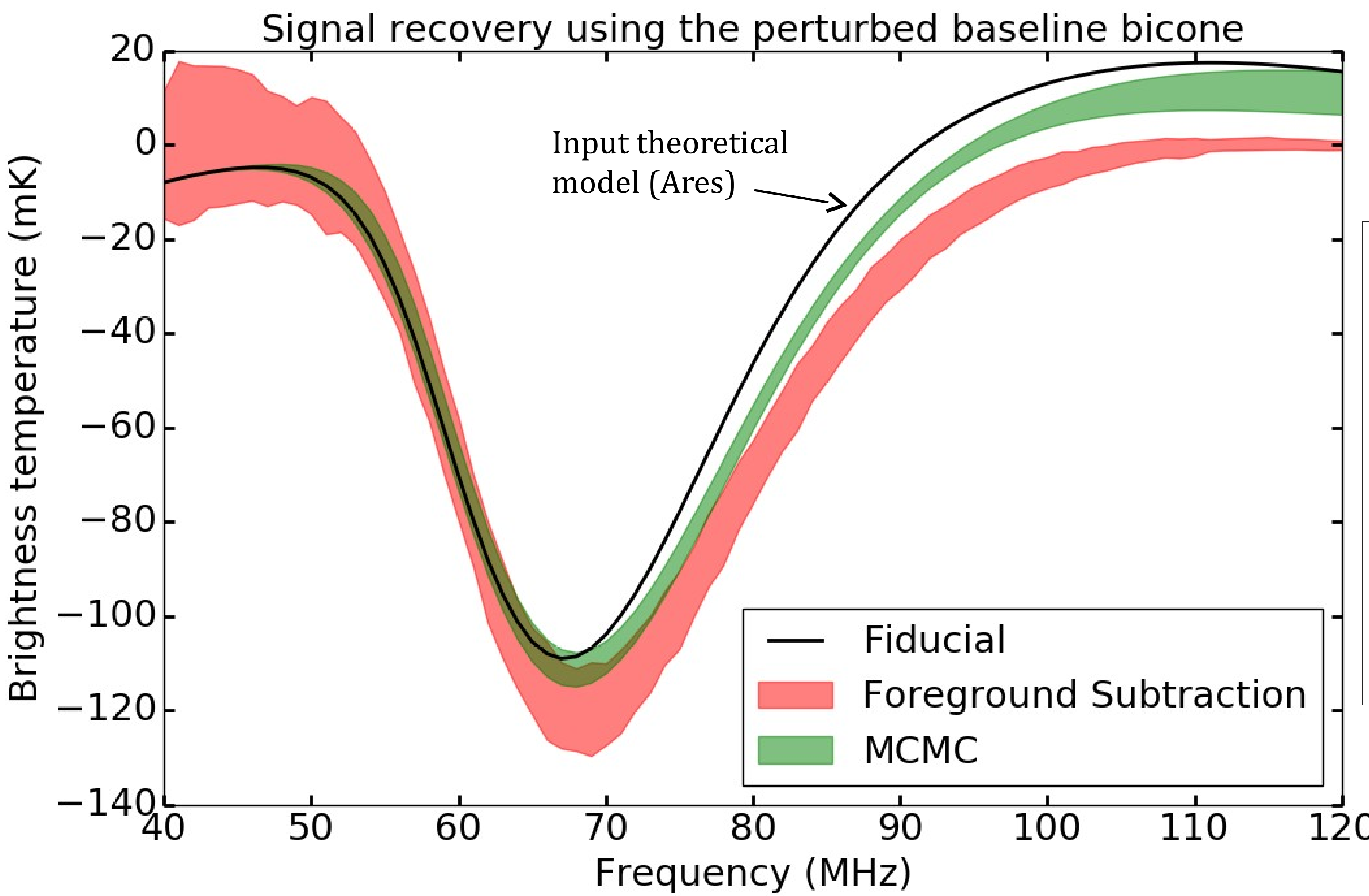
- Use of a Bayesian, neural network algorithm to simultaneously fit multiple analytic models (MCMC)
- Requires confidence in the models for undesired signals and systematic effects
- Model residuals must be noise-like below the sensitivity threshold

MCMC = Markov Chain Monte Carlo

Dynamical Filtering

- Mark undesired signals and systematic effects through dynamic modulation
- Effects are isolated through dynamical Fourier analysis
- Spectra of undesired signals can be measured separately
- Bayesian techniques can also be used to improve sensitivity

Updated Approach to Foreground Subtraction using Ball Thermally Perturbed Antenna Beam



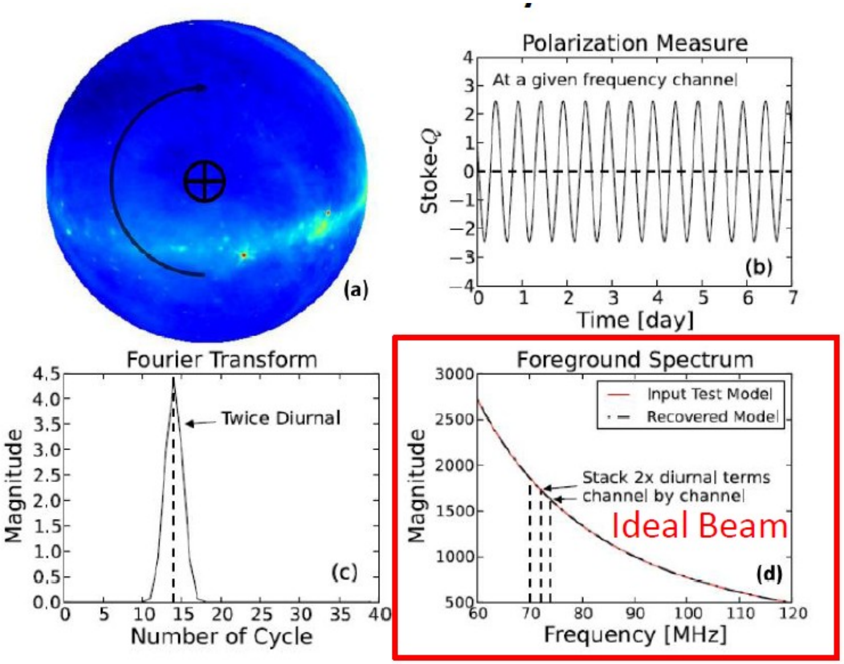
- Guzman 45 MHz quiet sky region, constant spectral index.
- Ball perturbed antenna beam.
- Ares 21-cm Global Signal model, 3 Turning Points.
- 1000 hrs integration.
- 5th order polynomial fit to the “wings” at high & low **ν subtracted.**

Instrument Requirement: Accurate Measurement of Antenna Beam

DARK AGES RADIO EXPLORER

Keith Tauscher & Jack Burns

Value Added through Polarimetry



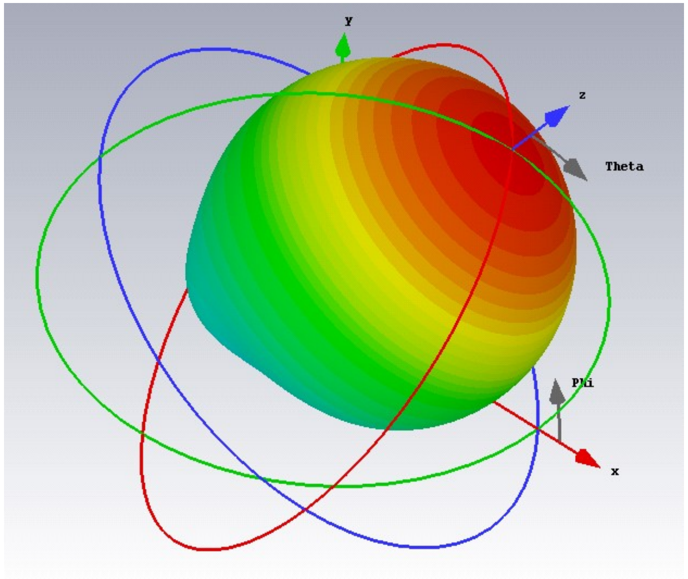
The Science Instrument Requirements

- 40-120 MHz band with <50 kHz resolution
- Full Stokes measurements while rotating the spacecraft at 1 RPM
- Good E- and H-plane beam symmetry for polarimetry
- 1000 hours per pointing, several pointings

Calibration

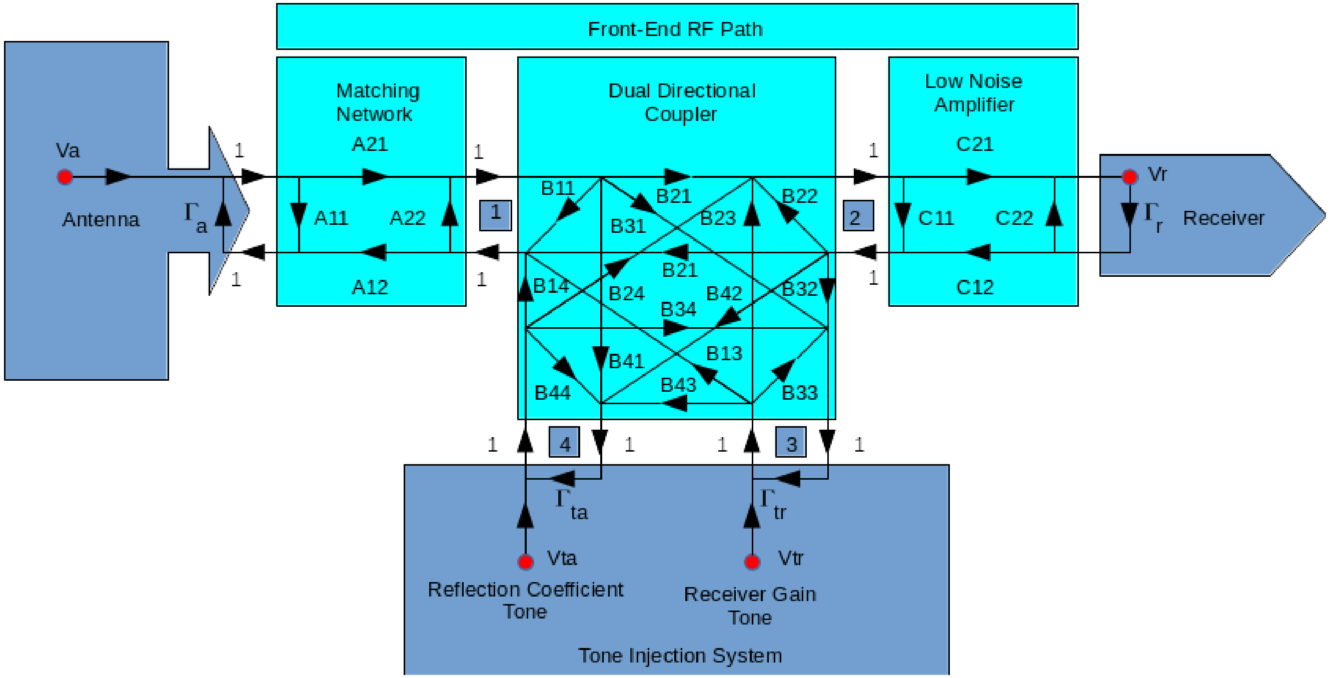
- Extensive electromagnetic and circuit simulations to establish baseline models
- Pre-flight measurements to confirm baseline models
- On-board measurements to track changes to baseline models
- Reflection coefficient, gain, and noise temperature known to 1 ppm
- Uncertainity in sky measurement must be less than 50 mK for MCMC

<u>EM Beam Modeling</u>



Dipole-like antenna with skirt

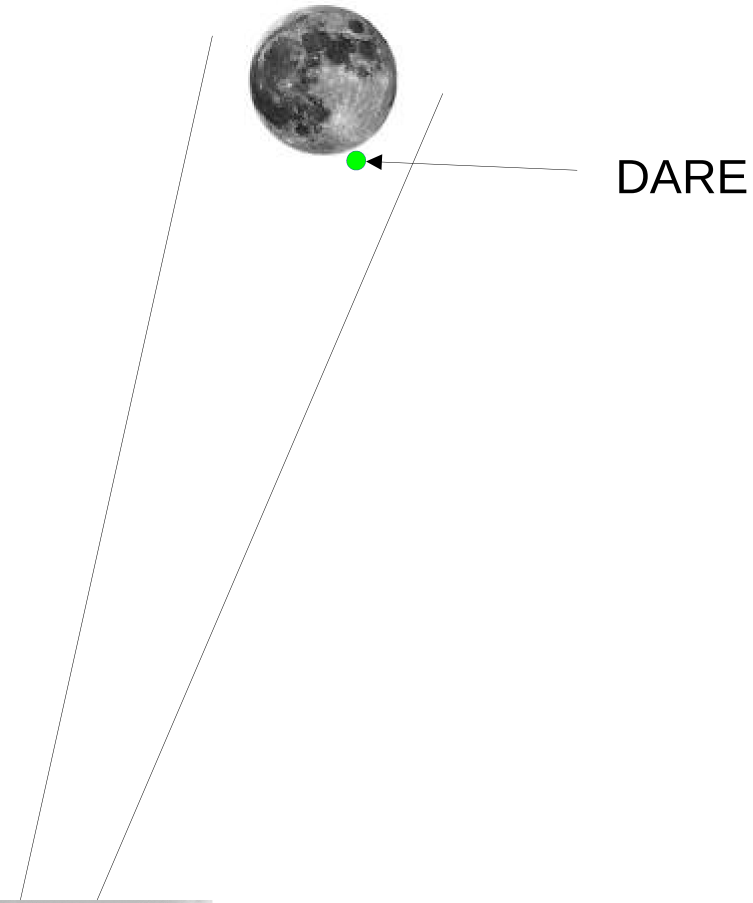
<u>S-parameter and Noise Parameter Network Models</u>



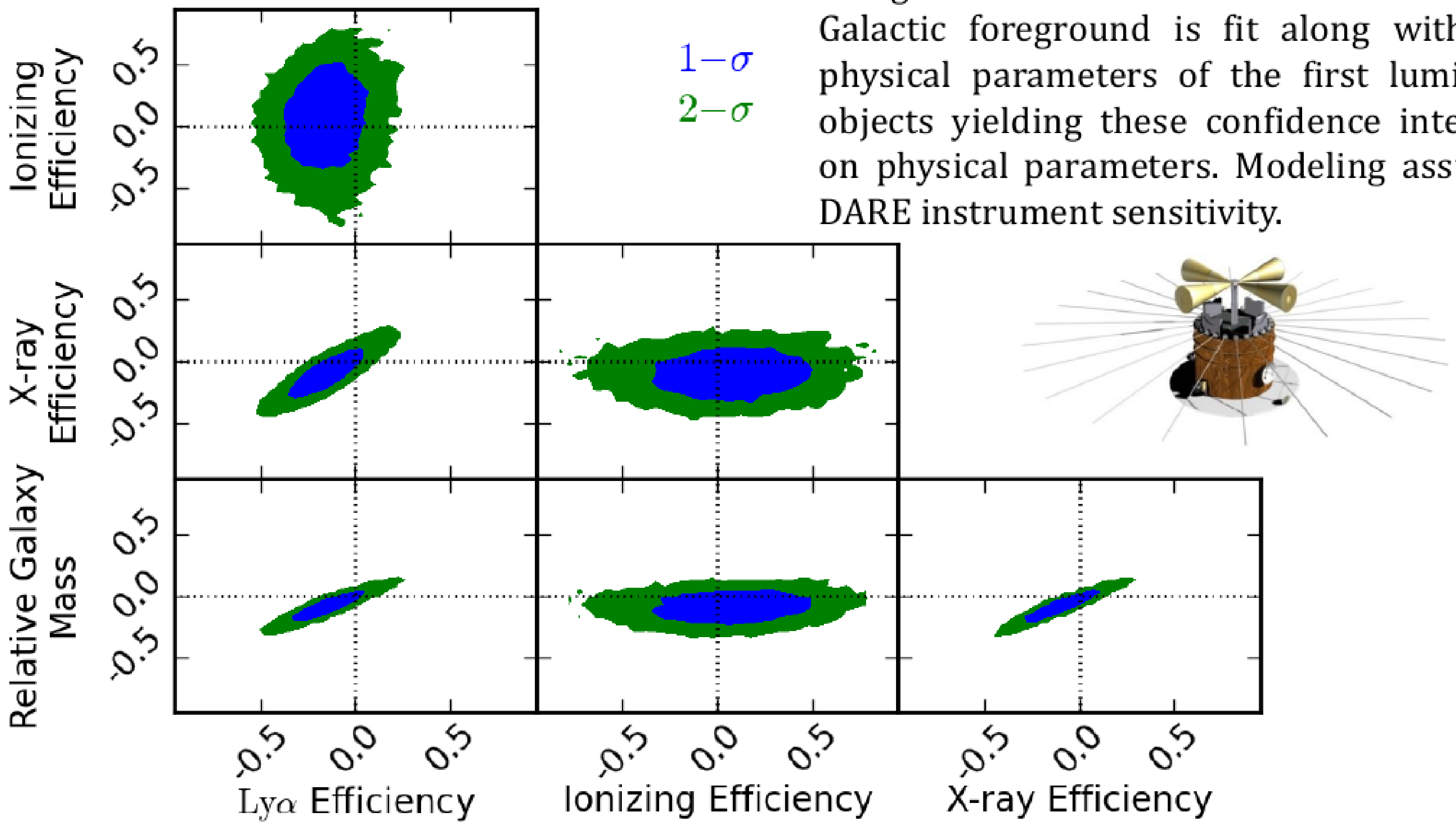
Tones and Noise Adding Radiometer

In Situ Beam Measurements

- Circularly polarized, PSK modulated carriers (6) are sent from ground to DARE
- DARE receives signals as the spacecraft orbits in front of the Moon to sweep beam
- Carrier levels are measured by DARE every 20 seconds to produce sampled beam cut
- A weak signal is also measured on its return trip to the Earth (Moon reflection) to estimate real-time path loss loss through the ionosphere



Characterizing the First Stars & Galaxies



Using an MCMC statistical framework, the Galactic foreground is fit along with the physical parameters of the first luminous objects yielding these confidence intervals on physical parameters. Modeling assumes DARE instrument sensitivity.

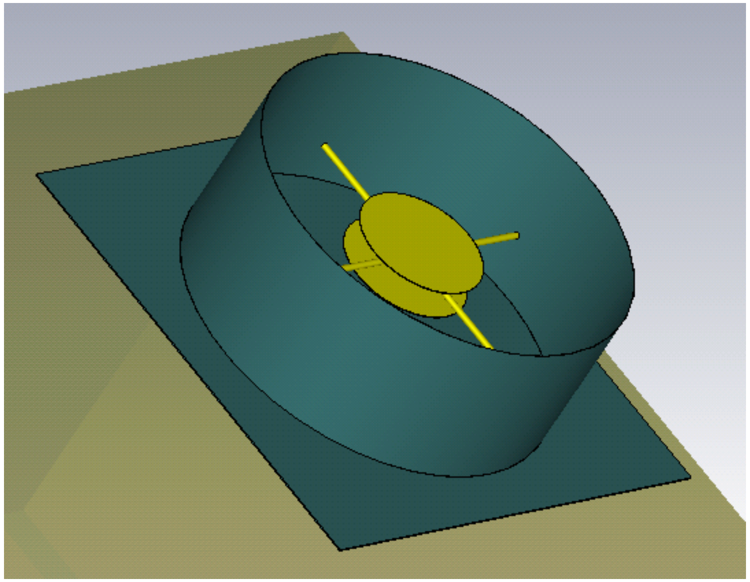
Global Experiments have the potential to bound the properties (e.g., mass, spectra) of the first generation of stars, black holes, & galaxies for the first time (0.1-0.2 dex).

Mirocha, Harker, & Burns (2015), *ApJ*, 813, 11.

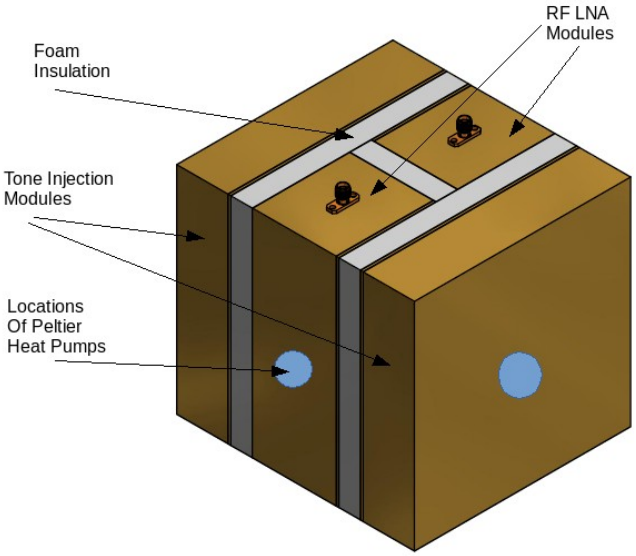
The Status

- **NASA Mid-Scale Explorer Proposal to be submitted in December 2016**
- **Preparations**
  - Strawman mission design completed – trade space identified
  - Extensive error analysis underway
  - Thermal analysis, power budget, orbital mechanics, etc.
  - Cosmic Twilight Polarimeter (CTP-v0.5)

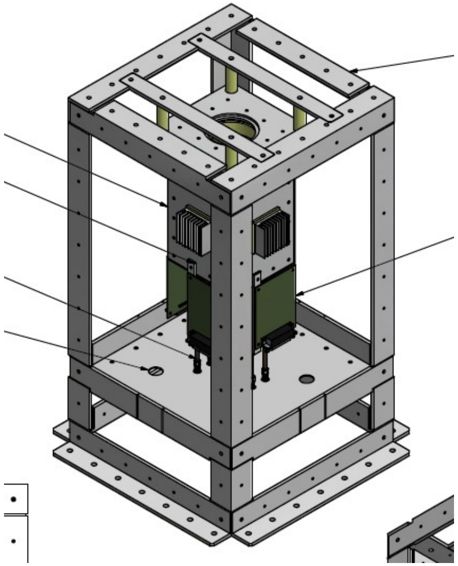
Sleeved Dipole with Skirt



Front-End Modules



Front-End Canister



Summary and Conclusions

The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environ at z > 10.

DARE science instrument: dual-pol, broad-band, dipole antenna, full Stokes total power receiver with tone and noise-adding calibration, and digital spectrometer.

MCMC fits set meaningful constraints on: Ly-alpha, ionizing, and X-ray backgrounds along with minimum virial temperatures of halos

DARE will be proposed in response to the NASA Explorer AO in late 2016.