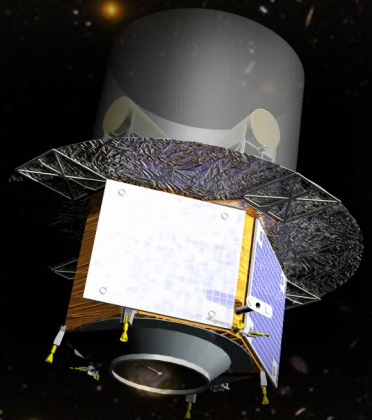
DARE

Cosmology from the Moon: The Dark Ages Radio Explorer

Jack Burns for the DARE Team

Center for Astrophysics & Space Astronomy

University of Colorado Boulder



DARE Project Team

Principal Investigator: Jack Burns, University of Colorado Boulder

Project Management & Mission Operations: NASA Ames Research Center: B. Hine & J. Bauman

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

Science Co-Investigators:

- Robert MacDowall, NASA GSFC, Project Scientist
- Richard Bradley, NRAO, Deputy Project Scientist
- Judd Bowman, Arizona State University
- Anastasia Fialkov, CfA
- Steven Furlanetto, UCLA
- Dayton Jones, Space Science Institute, Boulder
- Justin Kasper, University of Michigan
- Abraham Loeb, Harvard University
- Raul Monsalve, University of Colorado
- Jordan Mirocha, UCLA
- David Rapetti, University of Colorado Boulder
- Edward Wollack, NASA GSFC

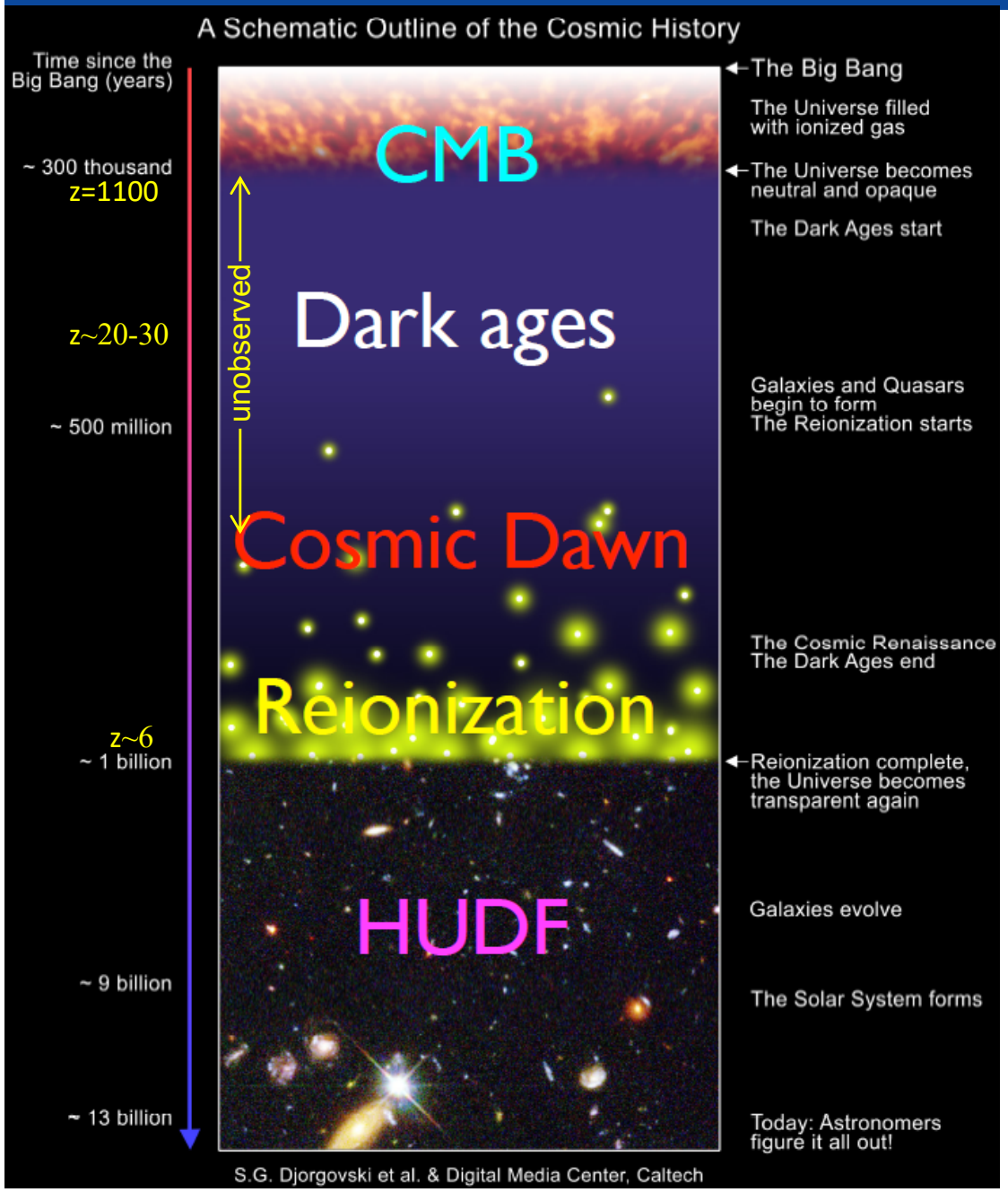
Collaborators:

- Michael Bicay, NASA Ames Research Center
- Abhirup Datta, University of Colorado Boulder
- Jonathan Pritchard, Imperial College
- Eric Switzer, NASA GSFC

Graduate Students:

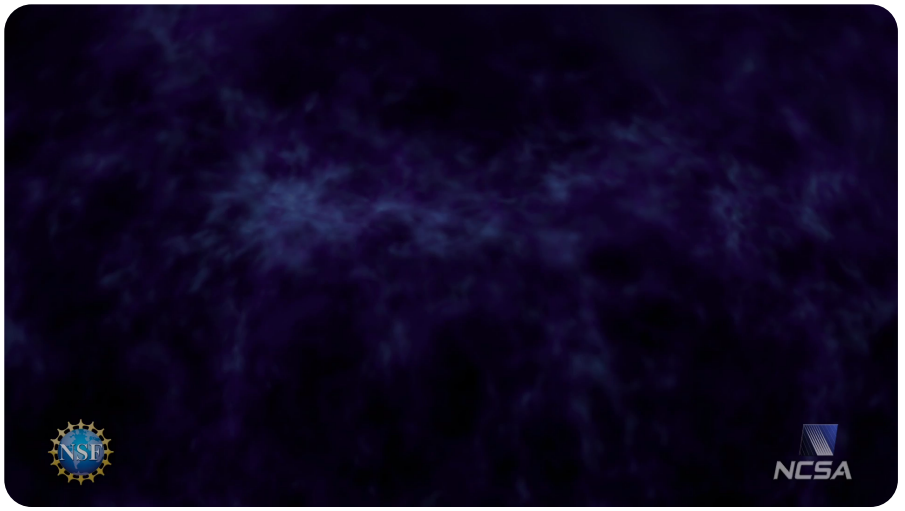
- Bang Nhan, University of Colorado
- Keith Tauscher, University of Colorado

The First Half-Billion Years



The First Stars

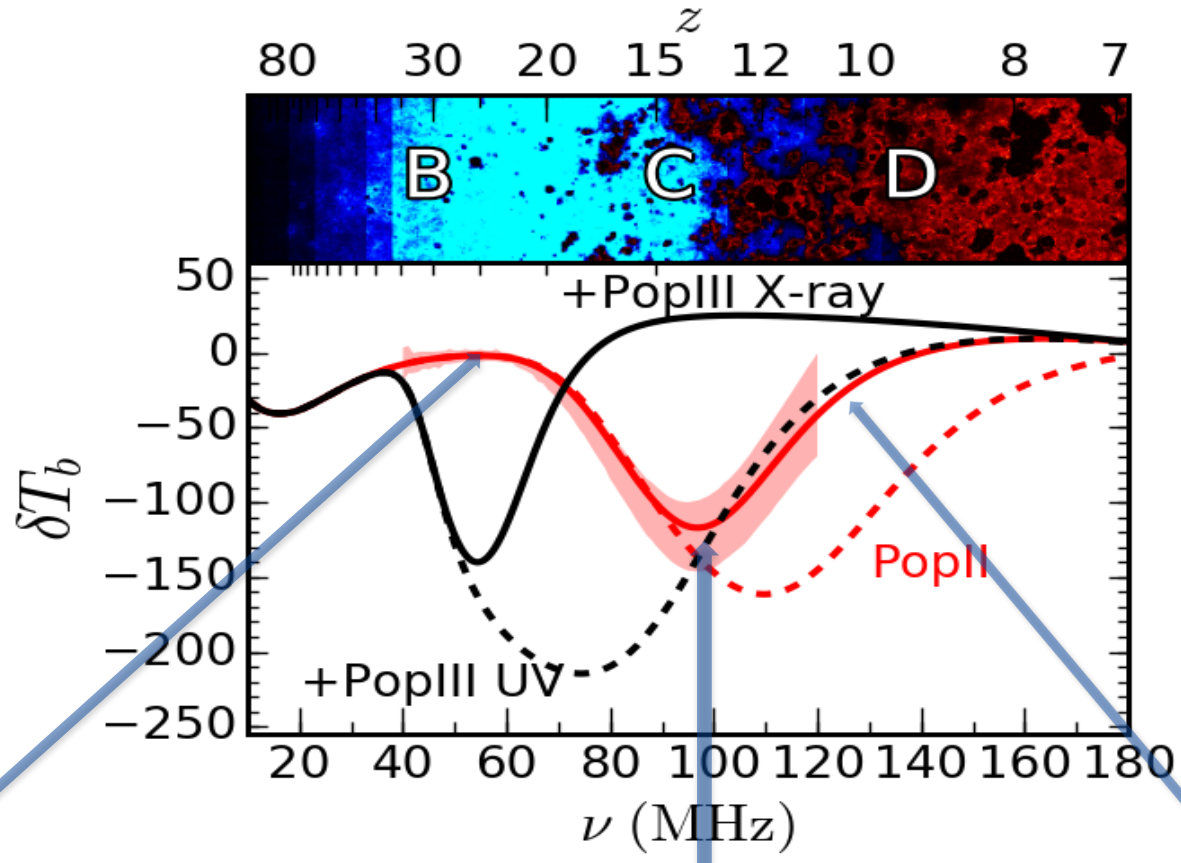
John Wise, Georgia Tech



DARE 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 decay, in the Dark Ages?

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 their characteristics?
- Is there evidence for exotic physics (e.g. Dark Matter decay) in the Dark Ages?

C: heating by first black holes

- When did the first accreting black holes turn on? What were their characteristics?

D: the onset of reionization

- What was the history of Reionization in the early Universe?

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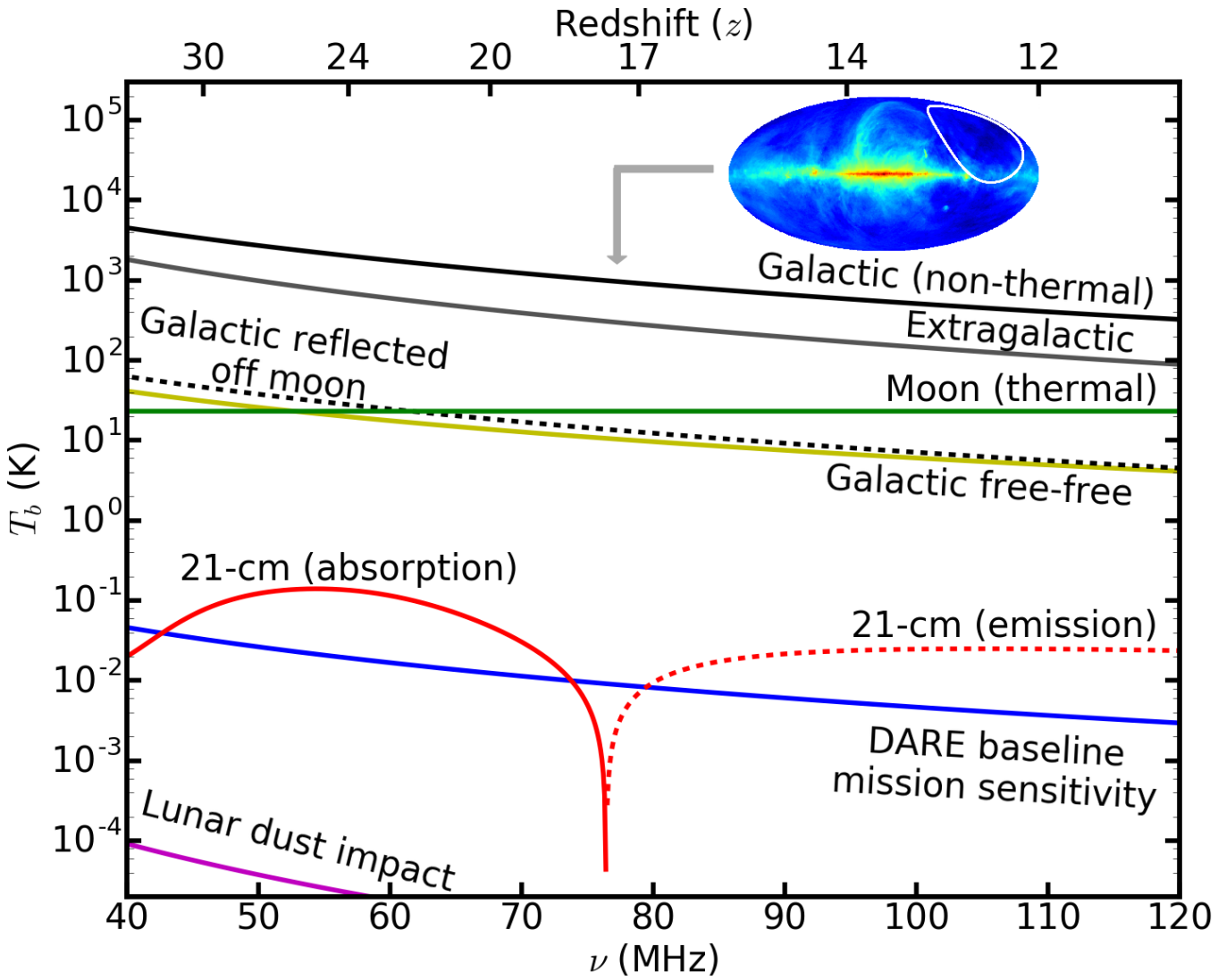
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006 and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

Foregrounds and Beam Chromaticity



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

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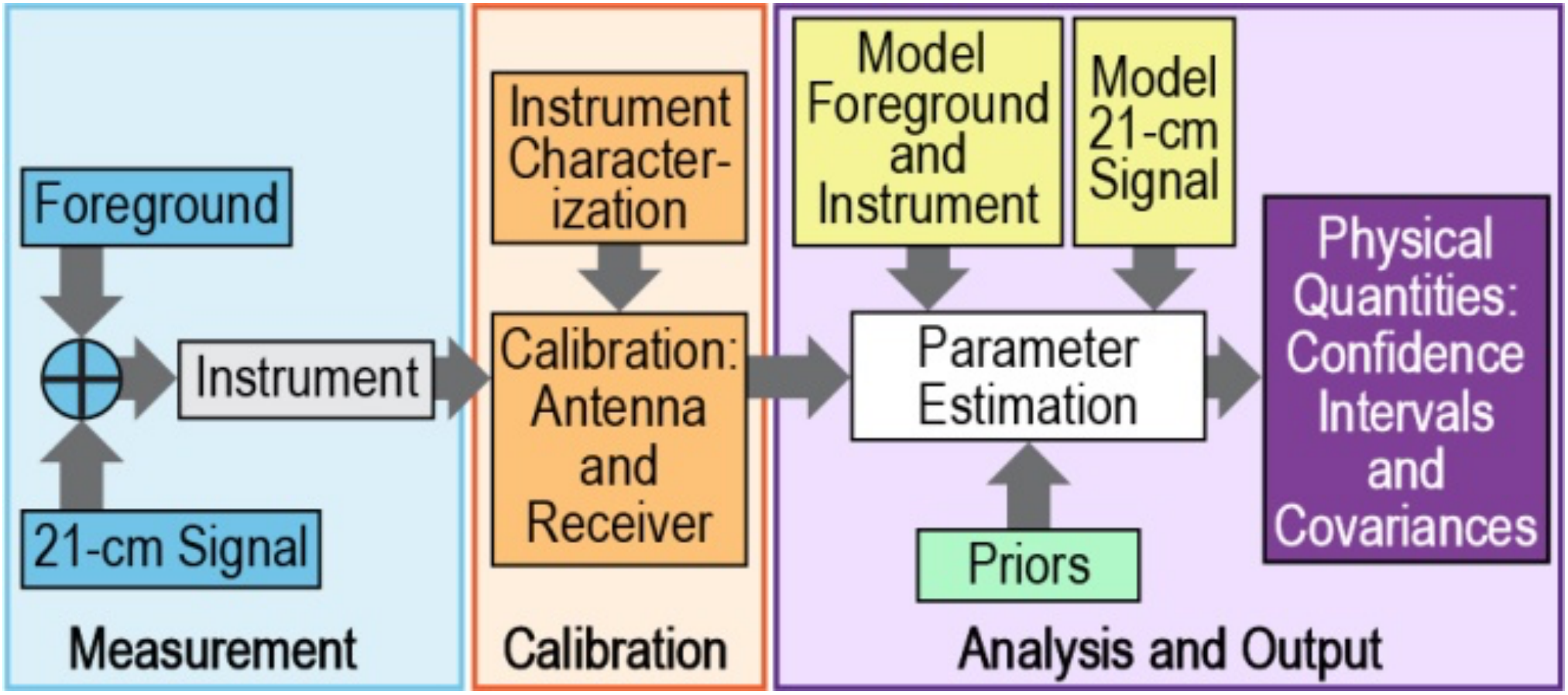
DARE observational strategy



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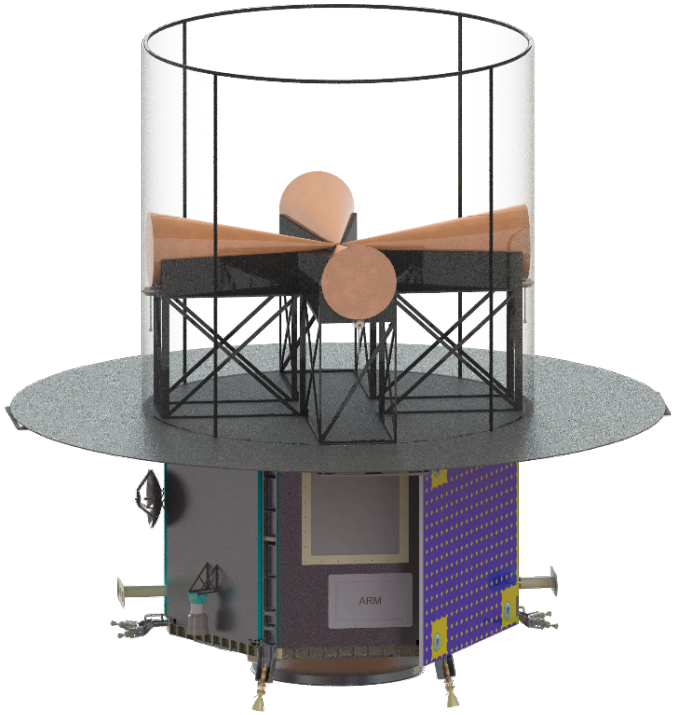
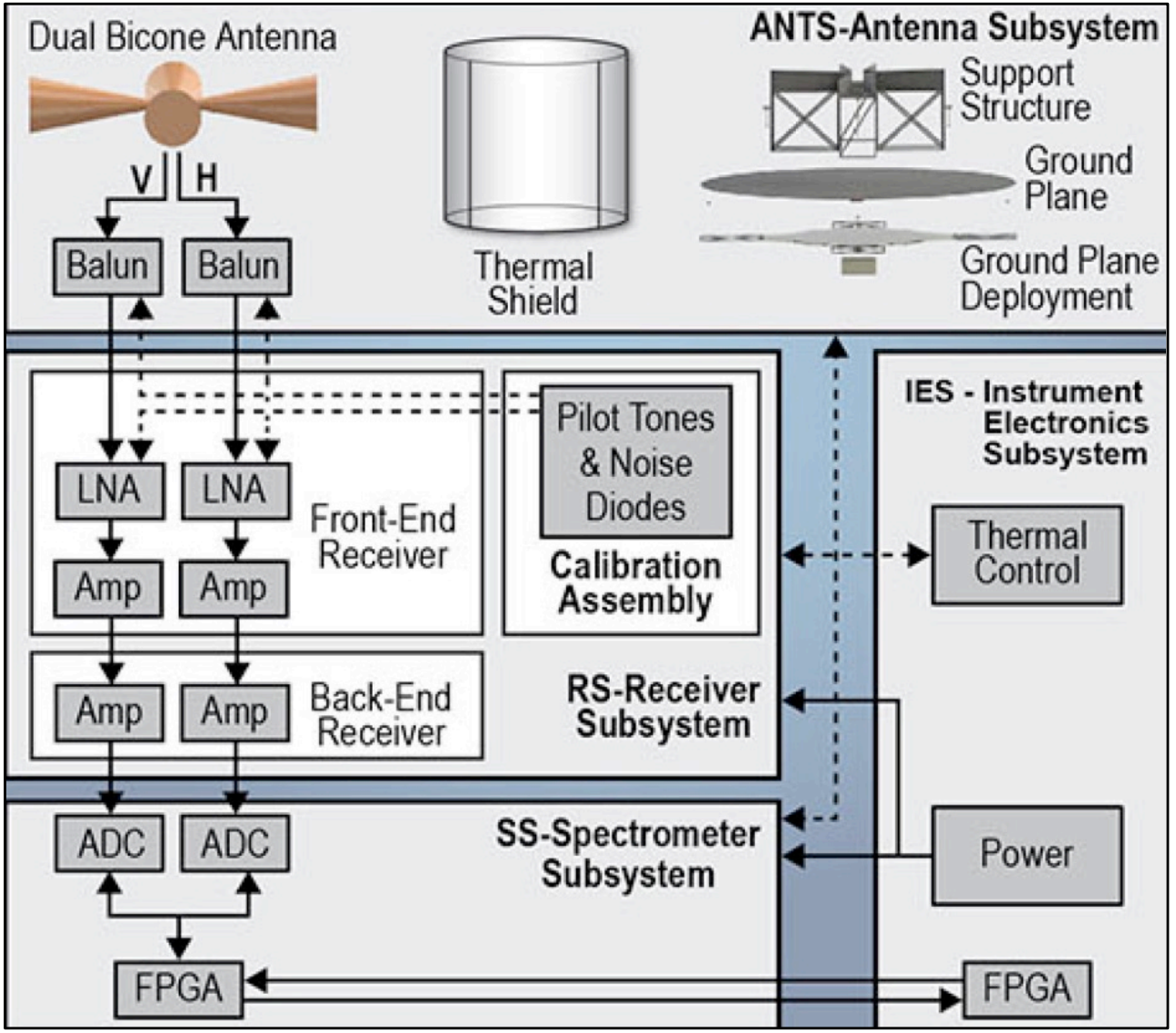
DARE Observatory

Two Year Mission Lifetime

- ~800 hrs integration above lunar farside.
- shielded from Sun.
- 50x 125 km elliptical, equatorial orbit.





DARE probes z=11-35 with ν=40-120 MHz

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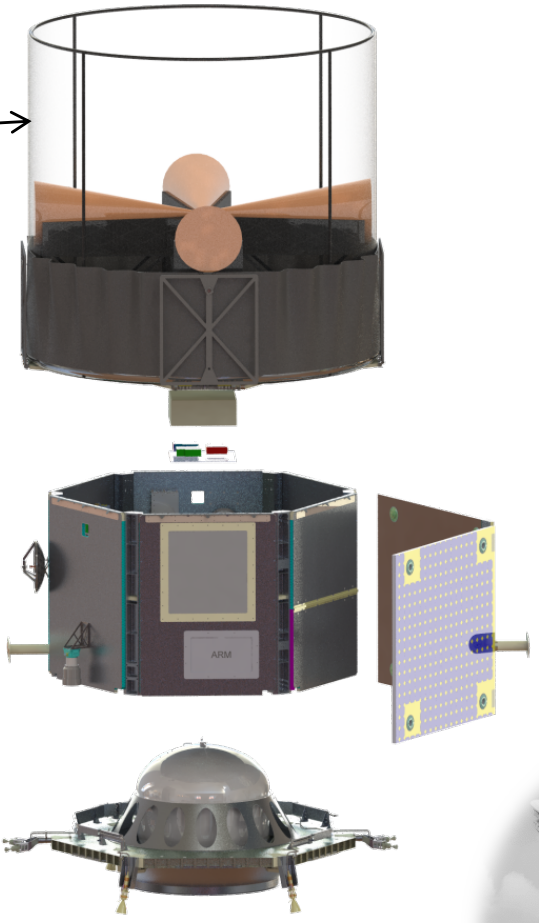
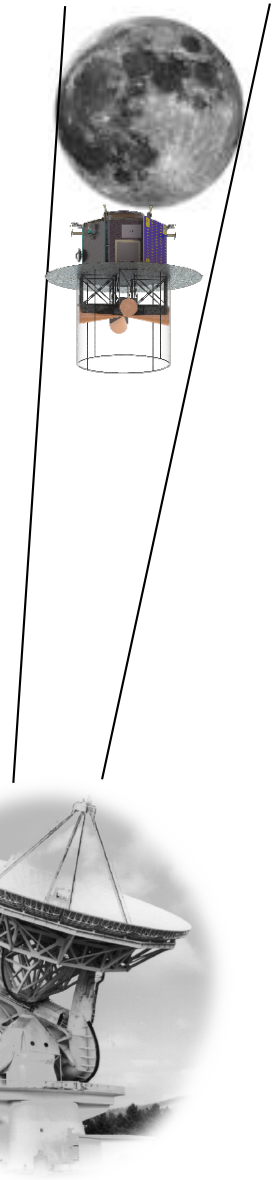
Chromaticity: Design Considerations

- Build antenna with low CTE material & minimize antenna thermal distortions (<10°C) with sunshade.
- Accurate modeling & measurement before launch.
- Measure beam on-orbit using frequency tones transmitted from Earth:
  - Circularly polarized, PSK modulated carriers (6) are sent from ground to DARE.
  - DARE receives signals as the spacecraft orbits above near side 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 through the ionosphere.





$$P_{echo} = \left(\frac{c^2}{64\pi^3}\right) \cdot \left(\frac{1}{\nu^2}\right) \cdot \left(\frac{P_t G_t^2 L_i^2 \sigma_m}{R_{t-M}^4}\right)$$ = echo power at 140-ft

Green Bank Observatory 140-ft antenna

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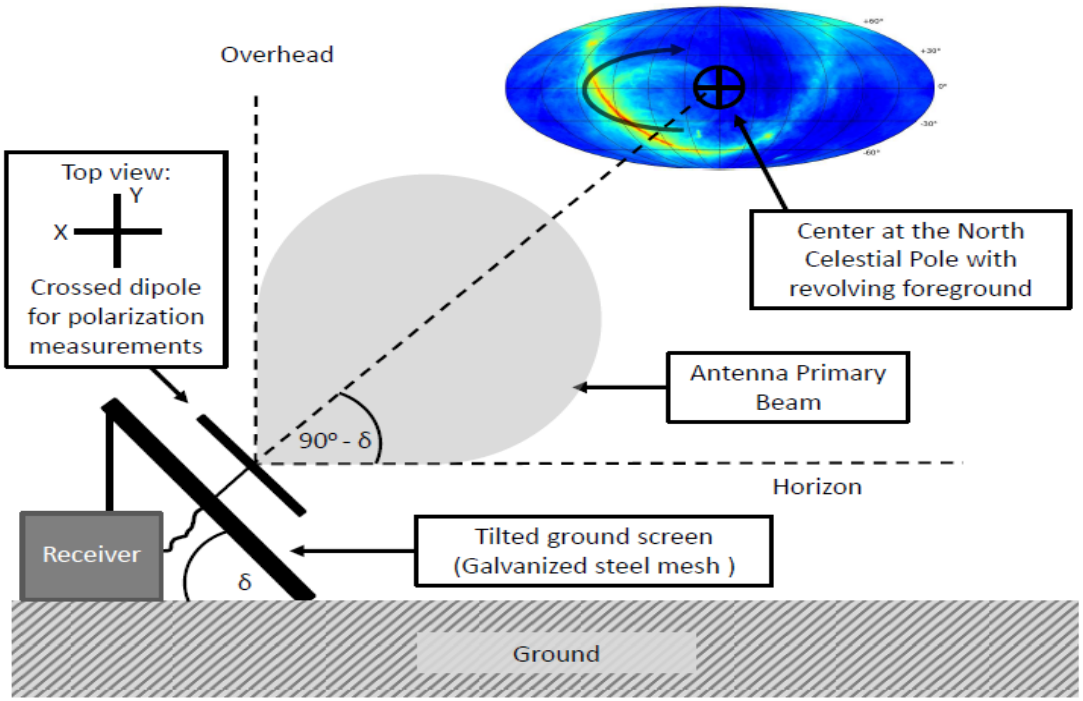
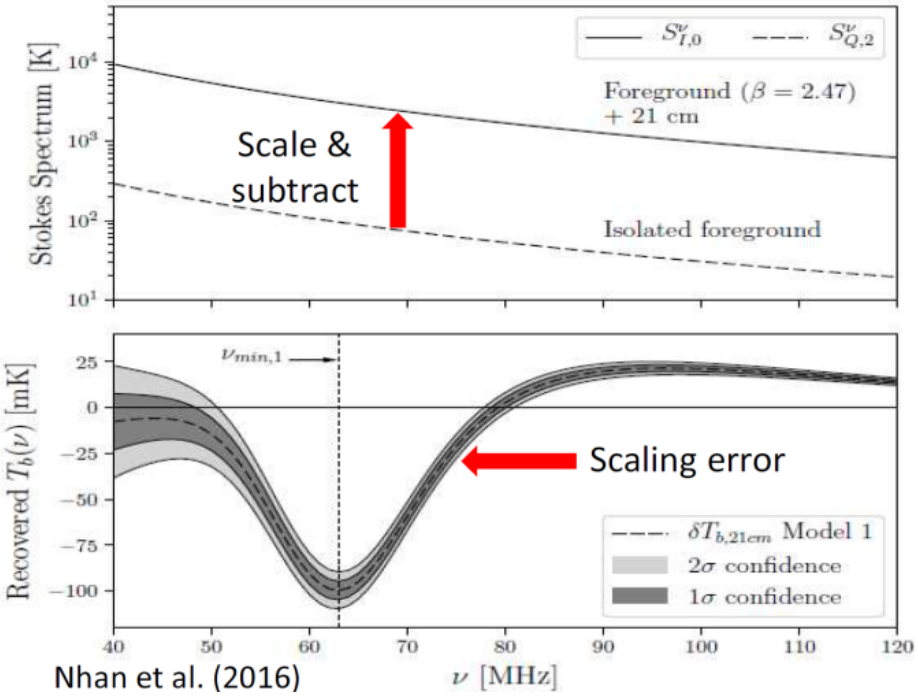
Polarimeter: Model-independent Foreground





Cosmic Twilight Polarimeter: Ground-based DARE Prototype

Polarimetry Process to measure Foreground

1. Measure "polarization leakage" caused by ν-dependence of power patterns of linearly polarized dipoles. Rotate spacecraft to measure modulated Stokes Q,U
2. Harmonic decomposition of modulated Q,U signal, scale to Stokes I, and subtract.

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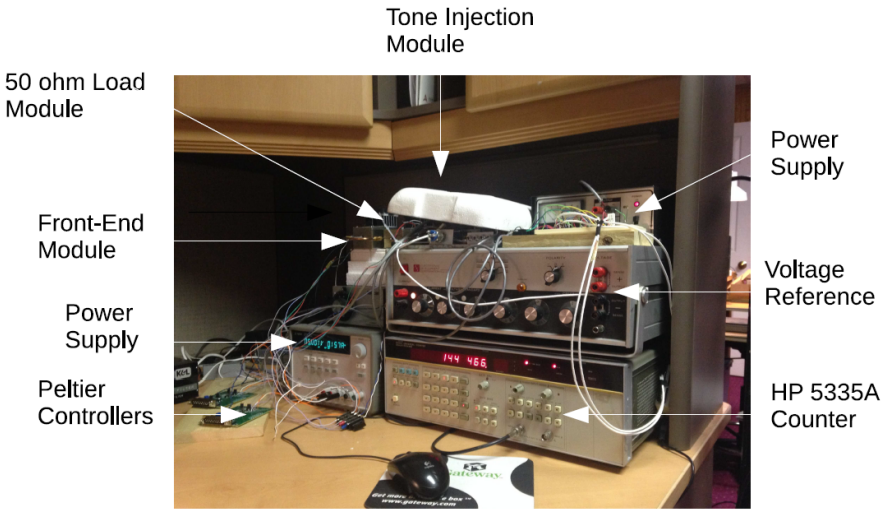
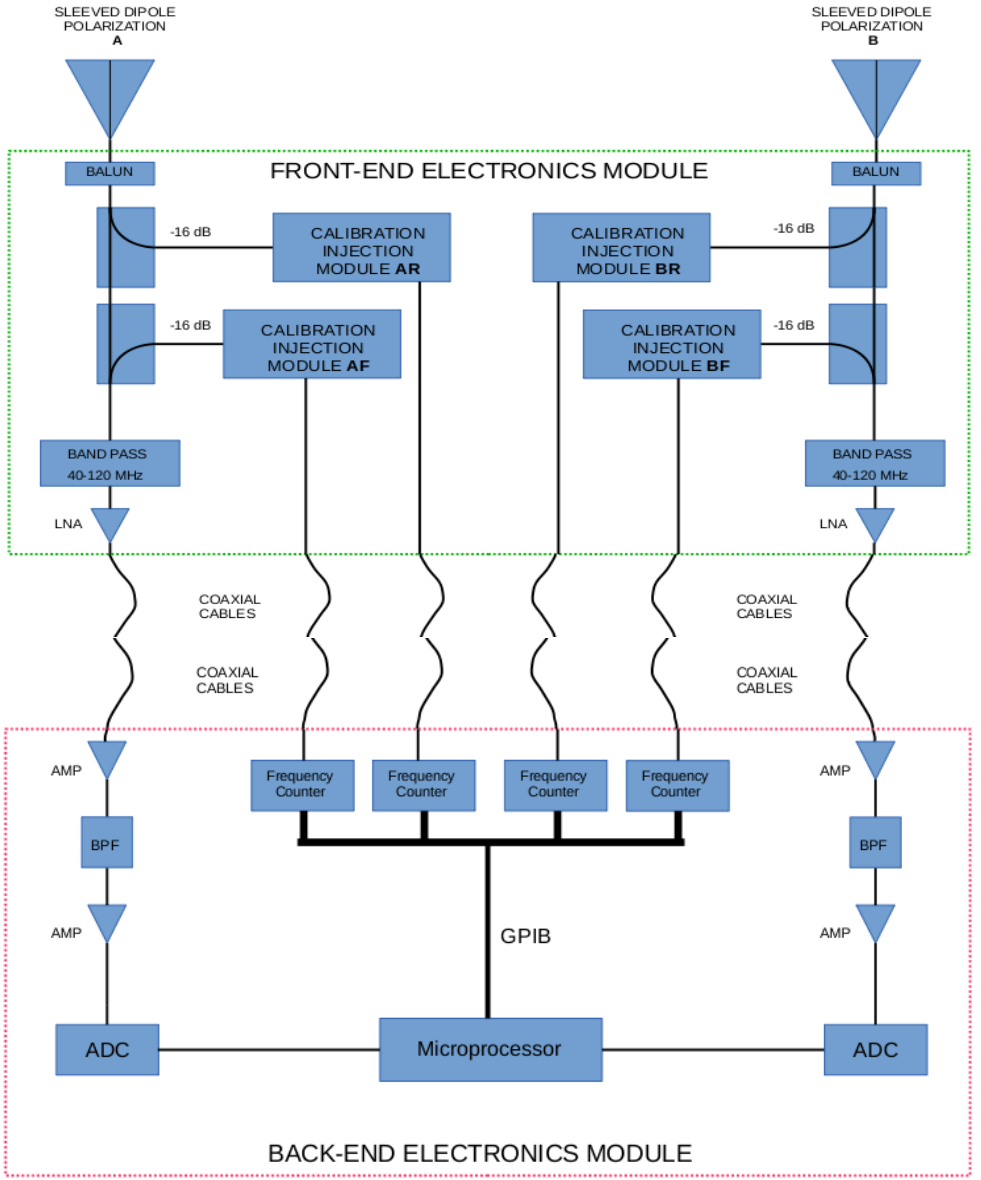
Nhan, Bradley, & Burns, 2017, ApJ, 836, 90.

Precision Calibration: Tone Injection

- Weak 21-cm signal against bright foregrounds requires high dynamic range measurement.
- Need precise measurements of gain drifts in the radiometer.
- Classical Dicke switching is not accurate enough.
- Narrow frequency tone (few kHz) injected. Voltage $\propto \nu_{tone}$ is measured with high fidelity – demonstrated in lab to 50 dB.





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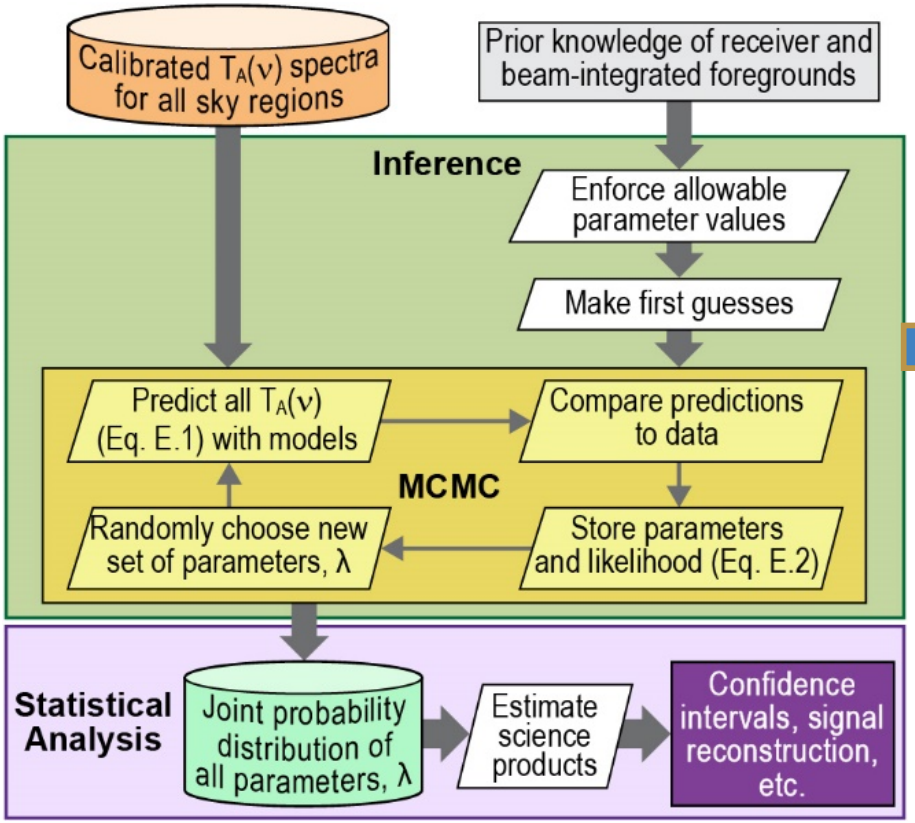
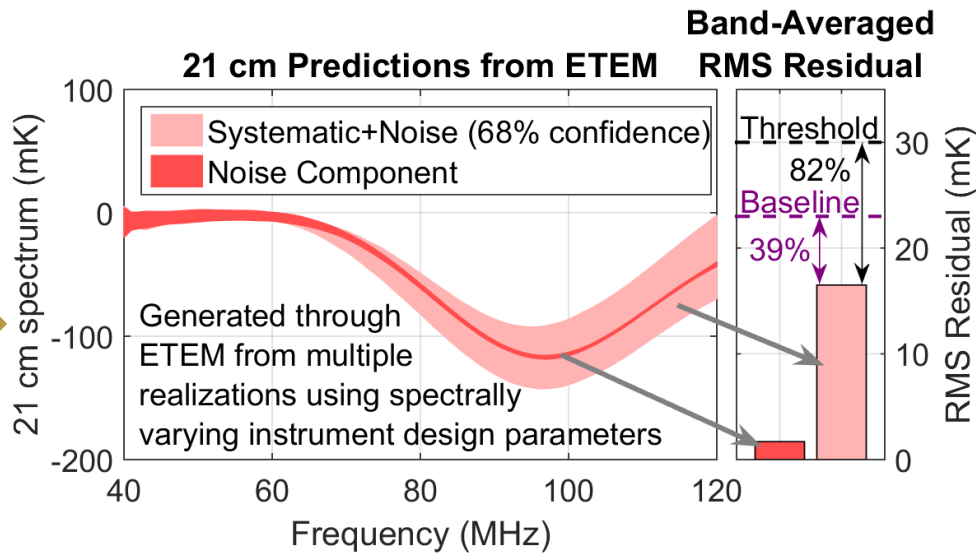
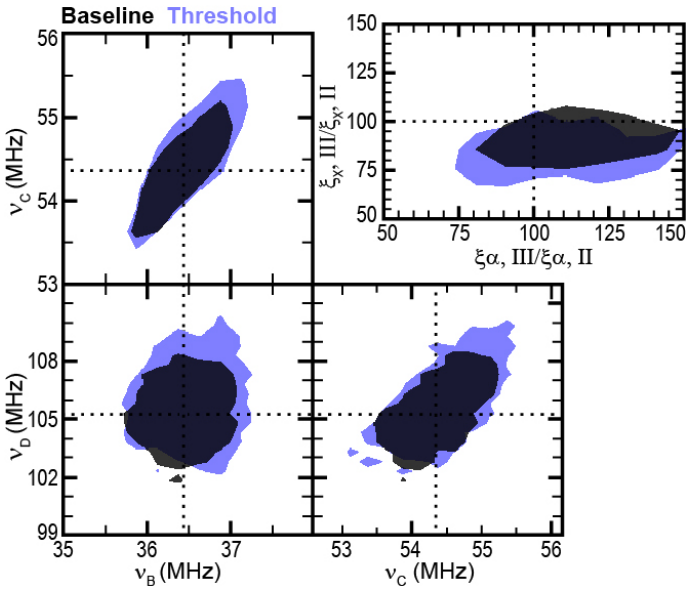
DARE Signal Parameter Pipeline: Parameter Estimation





Average RMS residual ~ 20 mK



$$T_{A,M}^{(r)} = \sum_i (\lambda_{21})_i f_i(\nu) + \sum_j (\lambda_{sys})_j^{(r)} g_j(\nu) \quad \text{Eq. E.1}$$

$$\ln L(\lambda) = -\frac{1}{2} \sum_r \sum_\nu \left[\frac{T_{A,D}^{(r)}(\nu) - T_{A,M}^{(r)}(\nu, \lambda)}{\sigma_r(\nu)} \right], \quad \text{Eq. E.2}$$

$$\sigma_r(\nu) = \frac{T_{A,D}^{(r)}(\nu)}{\sqrt{\Delta\nu \Delta t}}$$

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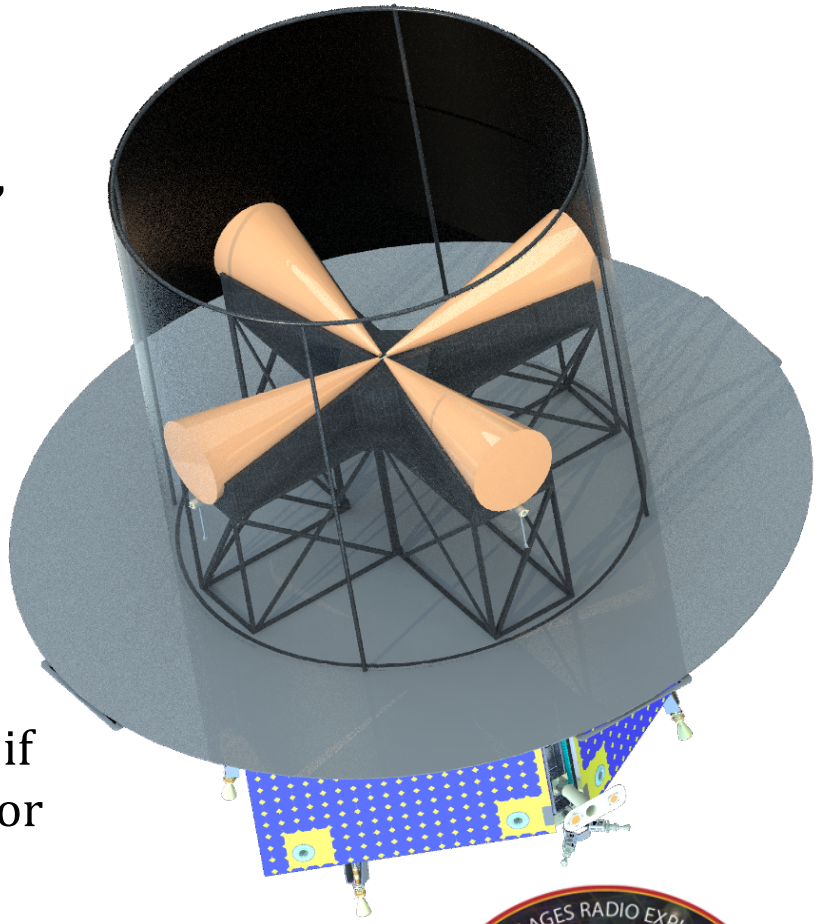
Summary and Conclusions

- The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environs at z>10.
- *DARE science instrument*: biconical dipole antenna, pilot-tone injection receiver, digital spectrometer, polarimeter.
- Challenge of observing weak 21-cm signal in presence of bright foreground is addressed via careful measurements of antenna beam & independent measure of foreground via polarimetry.
- *DARE will set meaningful constraints on:* Ly-α, ionizing, & X-ray backgrounds that will determine if Pop II or Pop III stars dominated the light output for the first galaxies.
- DARE has been submitted as a mission proposal to NASA's MIDEX program.



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