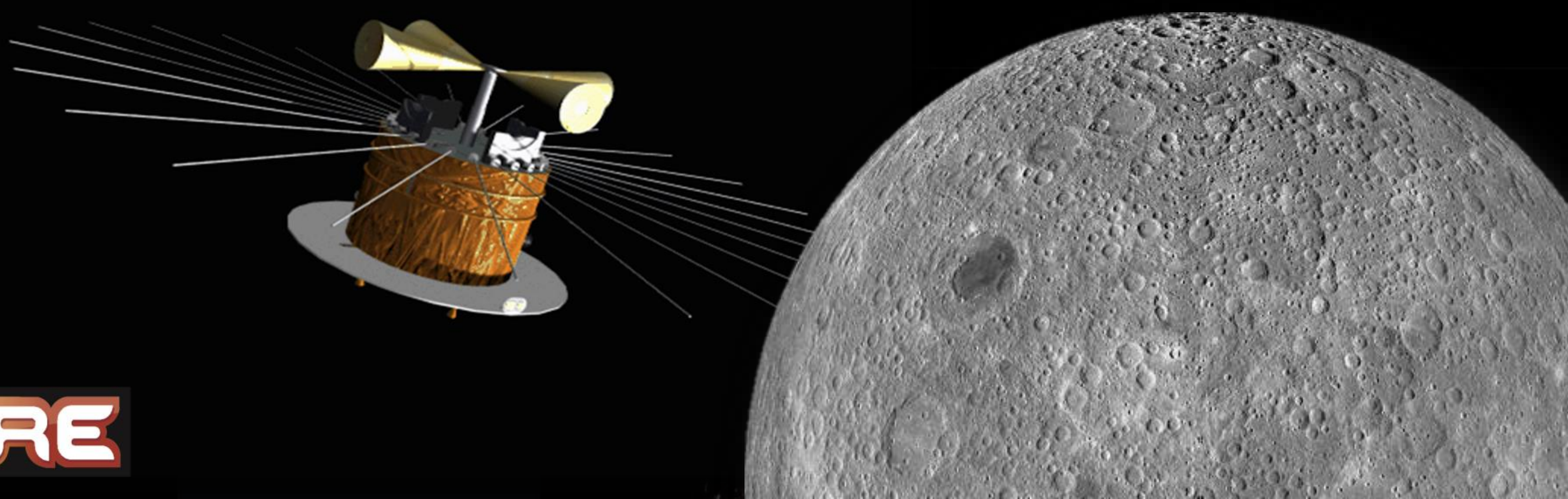
DARE

DARK AGES RADIO EXPLORER

Jack Burns for the DARE Team
Center for Astrophysics & Space Astronomy
University of Colorado Boulder



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DARE Project Team

Principal Investigator: Jack Burns, University of Colorado Boulder
Deputy Principal Investigator: Joseph Lazio, JPL/Caltech
Project Manager: Butler Hine, NASA Ames
Deputy Project Manager: Jill Bauman, NASA Ames
Spacecraft Project Manager: John Jonaitis, Ball Aerospace
Instrument Project Manager: Karen Lee, JPL/Caltech

Science Co-Investigators:

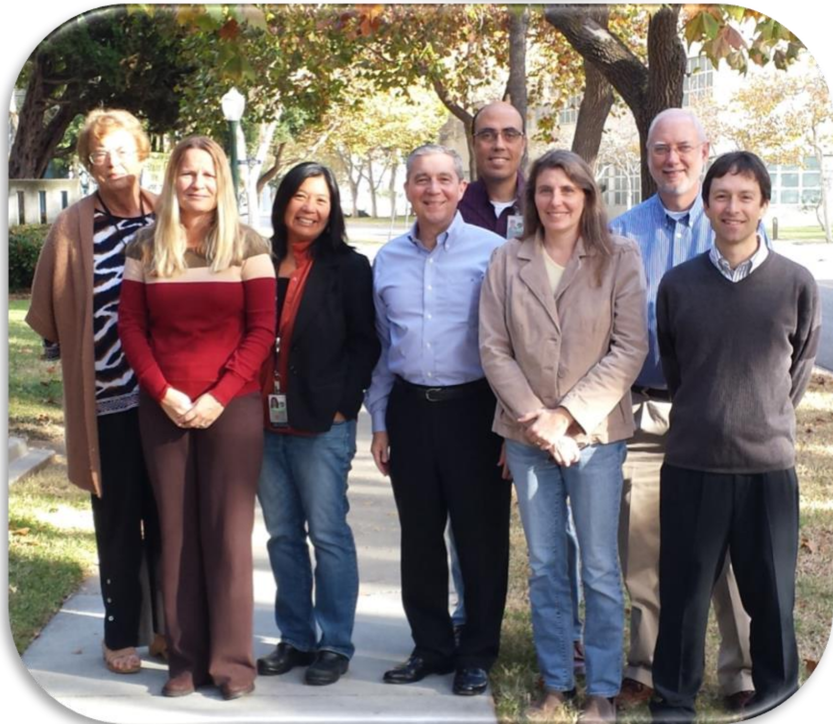
- Judd Bowman, Arizona State University
- Richard Bradley, National Radio Astronomy Observatory
- Abhirup Datta, University of Colorado Boulder
- Steven Furlanetto, UCLA
- Dayton Jones, JPL/Caltech
- Justin Kasper, University of Michigan
- Abraham Loeb, Harvard University

Collaborators:

- Michael Bicay, NASA Ames
- Geraint Harker, University College London
- Jonathan Pritchard, Imperial College
- Michael Seiffert, JPL

Graduate Students:

- Jordan Mirocha, University of Colorado
- Bang Nhan, University of Colorado



The Ball DARE Team

- Bill Purcell, Ball Proposal Manager
- John Jonaitis, Spacecraft Project Manager
- Brett Landin
- Dave Ruppel
- Jeremy Stober
- Scott Mitchell
- Lisa Hardaway

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Ball Aerospace & Technologies Corp.

Outline of the Presentation

- DARE Science Objectives
- The Case for Space: Human-generated RFI & Earth's Ionosphere.
- DARE Baseline Mission Concept
  - Spacecraft, launch, & trajectory
  - Radiometer
  - Engineering Prototype
- Foreground Removal & Signal Extraction
- Synergies with other telescopes

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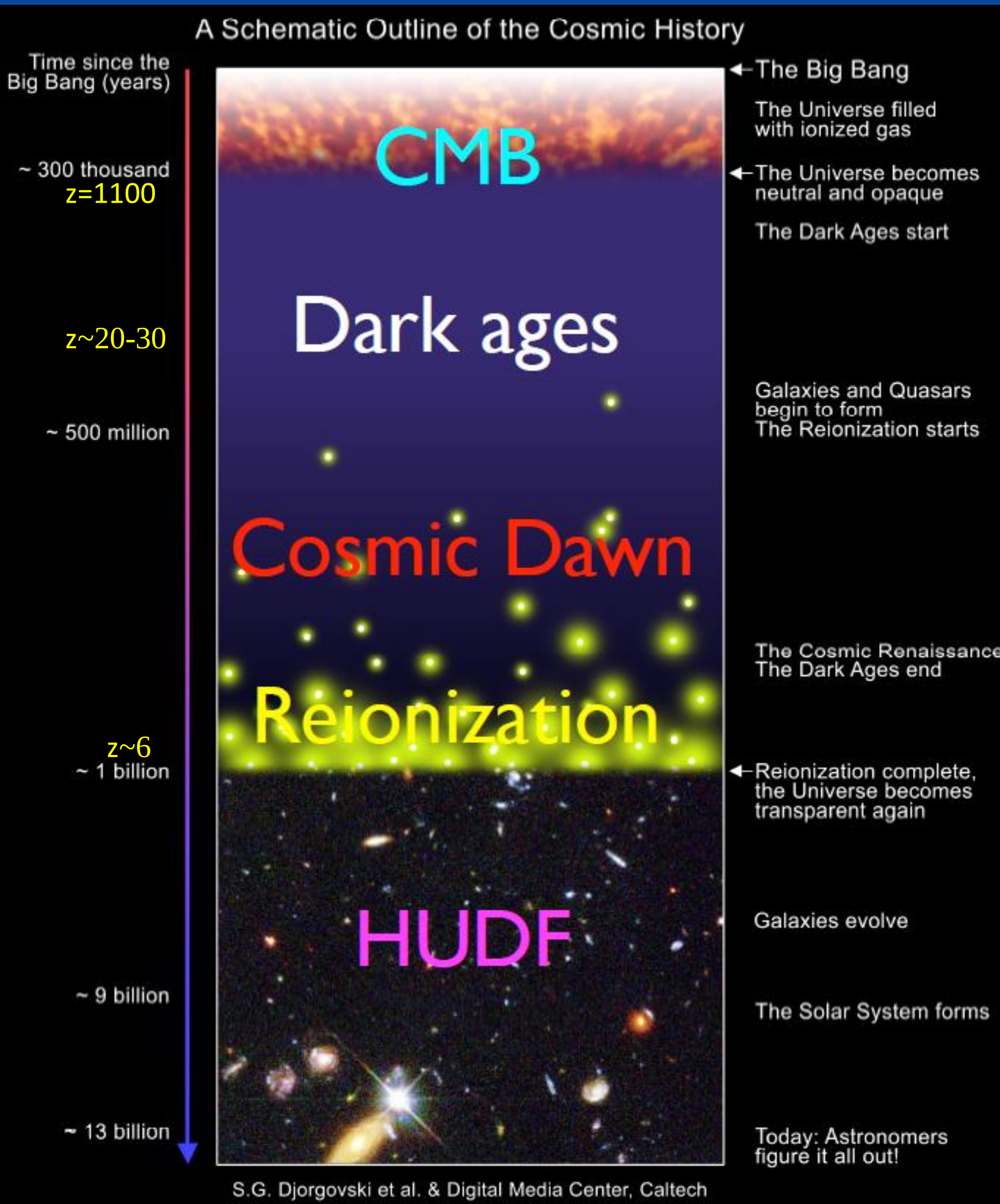
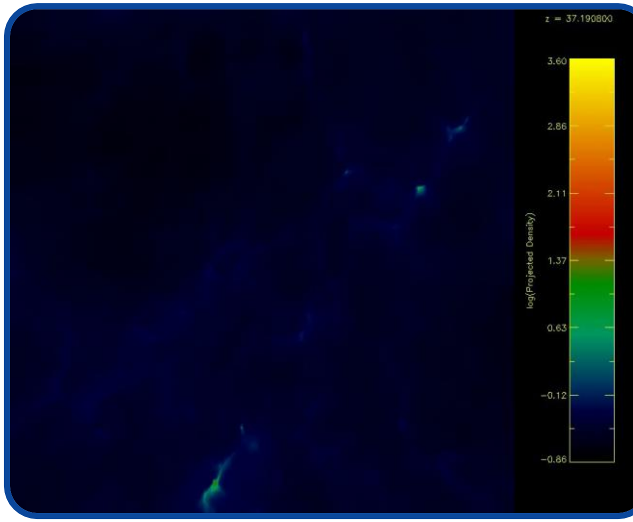
The First Half-Billion Years



The First Stars

John Wise, Georgia Tech



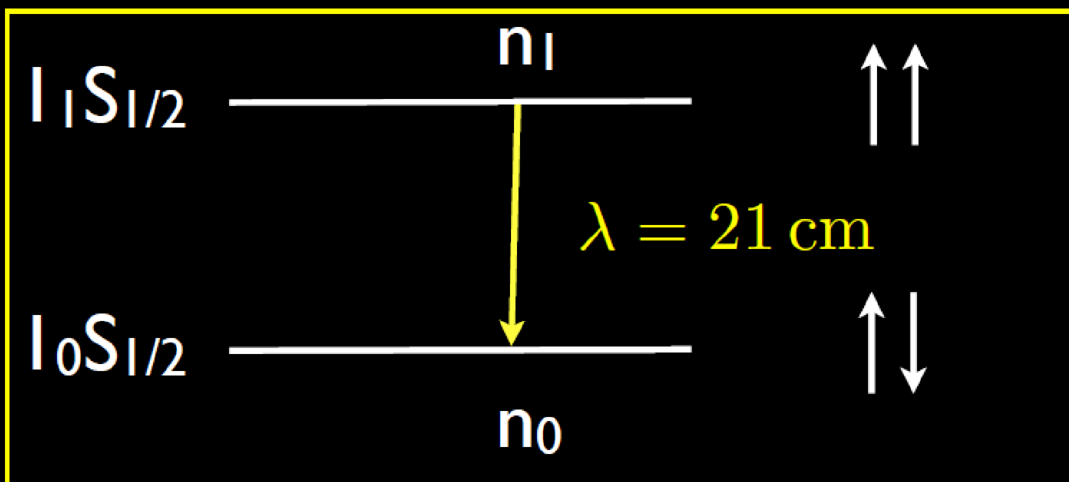
Dare Science Questions

- When did the First Stars ignite? What were these First Stars?
- When did the first accreting Black Holes turn on? What was the characteristic mass?
- When did Reionization begin?
- What surprises emerged from 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

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

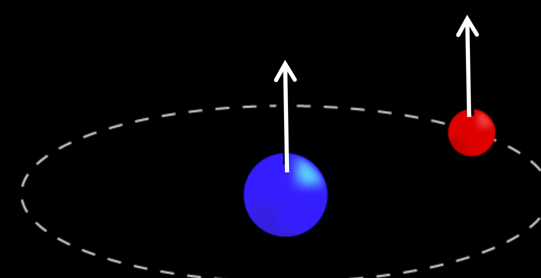
Useful numbers:

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

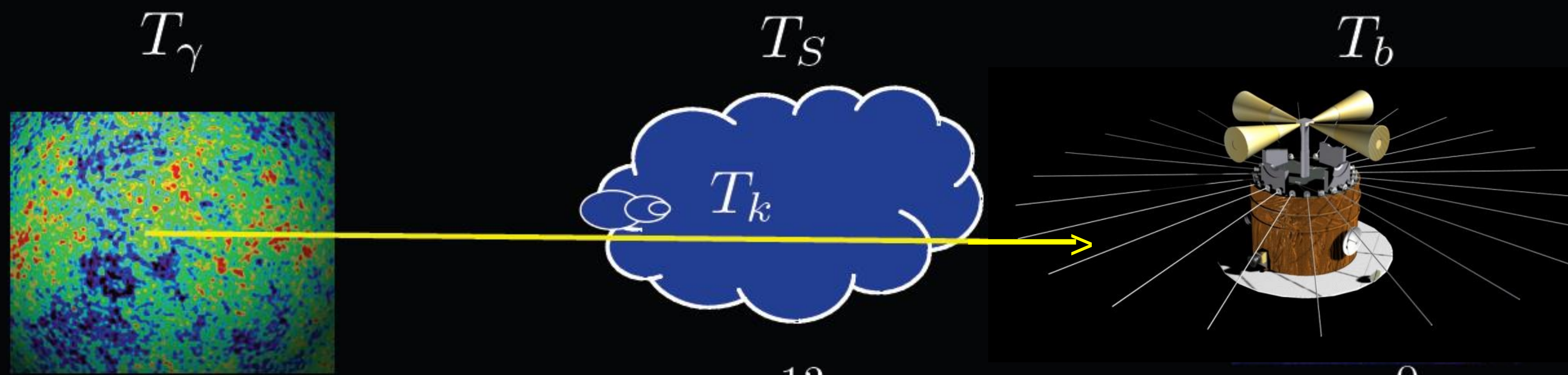
$$t_{\text{Age}}(z = 6) \approx 1 \text{ Gyr}$$

$$t_{\text{Age}}(z = 10) \approx 500 \text{ Myr}$$

$$t_{\text{Age}}(z = 20) \approx 150 \text{ Myr}$$



The 21-cm Line in Cosmology



$z = 13$

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

$z = 0$

$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature ($P=kT_b\Delta\nu$)

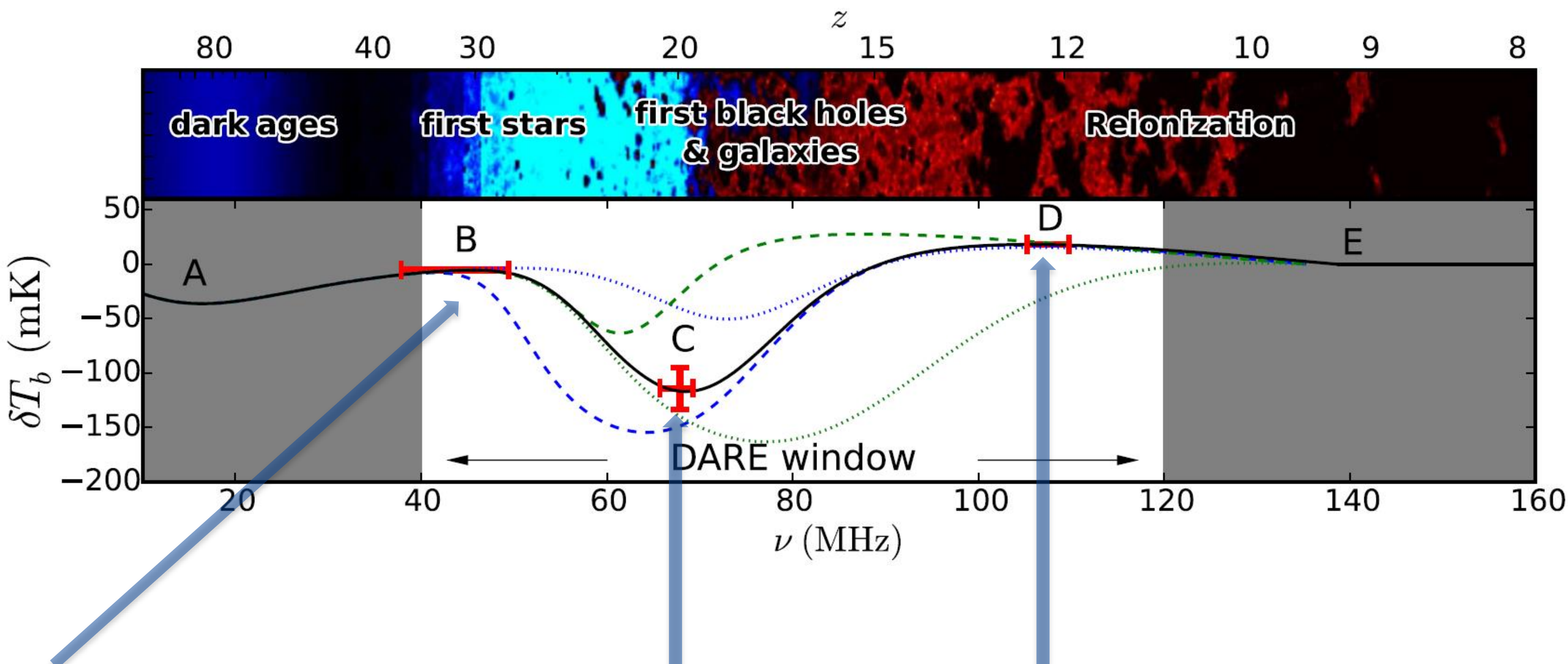
$$T_b = 27 x_{\mathrm{HI}} (1+\delta_b) \left(\frac{T_S - T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

spin temperature set by different mechanisms:

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

Courtesy of J. Pritchard

DARE will focus on determining or constraining *Turning Points* B, C, D



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

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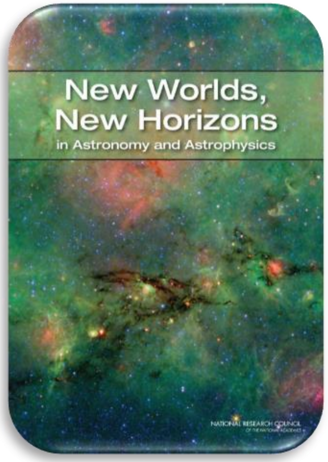
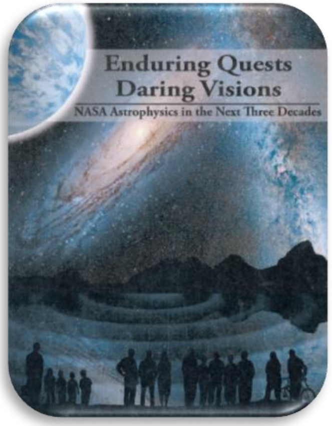
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D*, 82, 023006

Astrophysics Decadal Survey & Astrophysics Roadmap identify Cosmic Dawn as a top Science Objective

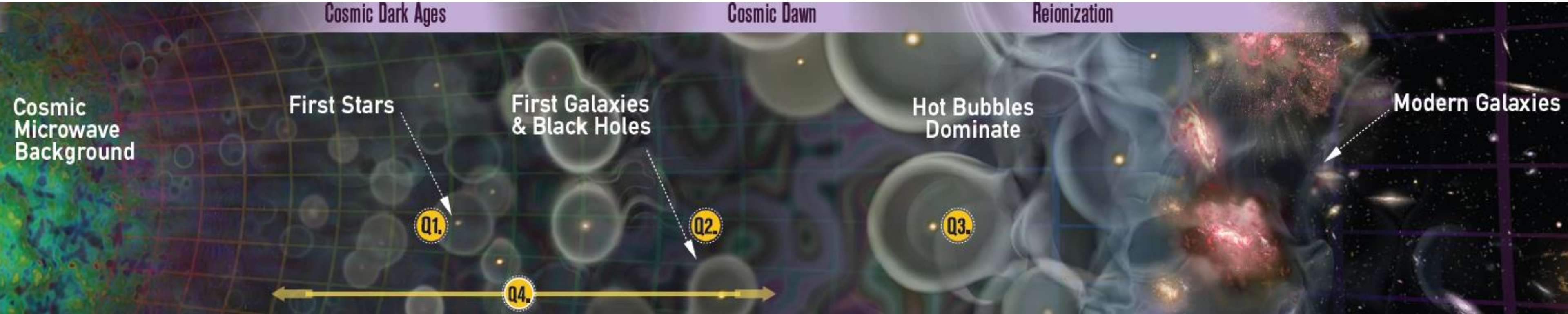


- "A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?" *New Worlds, New Horizons (NRC 2010)*



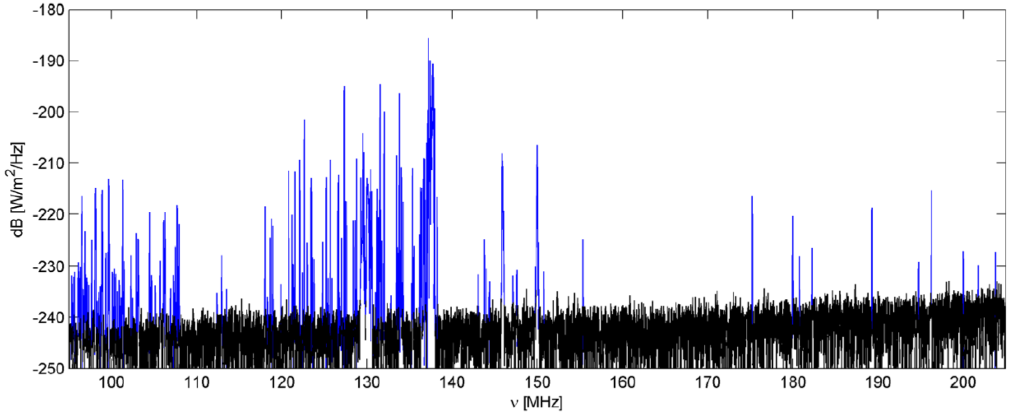
- How Does our Universe Work? Small Mission: "Mapping the Universe's hydrogen clouds using 21-cm radio wavelengths via a lunar orbiter observing from the farside of the Moon" *NASA Astrophysics Division Roadmap (2013)*

"What were the first objects to light up the Universe and when did they do it?" We can uniquely address this mystery with DARE in orbit above the lunar farside.



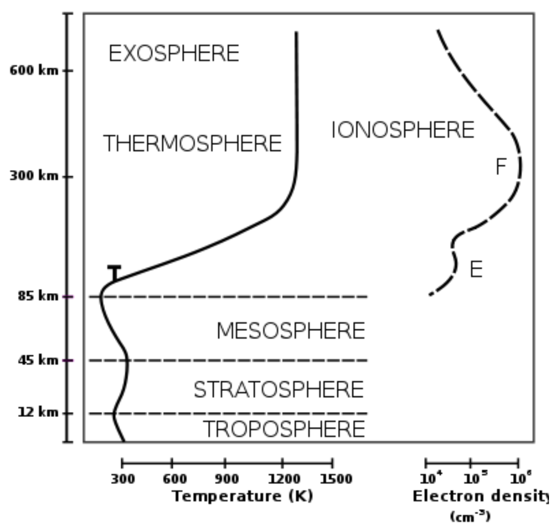
The Case for Space

Human-generated Radio Frequency Interference (RFI)



and

Earth's Ionosphere



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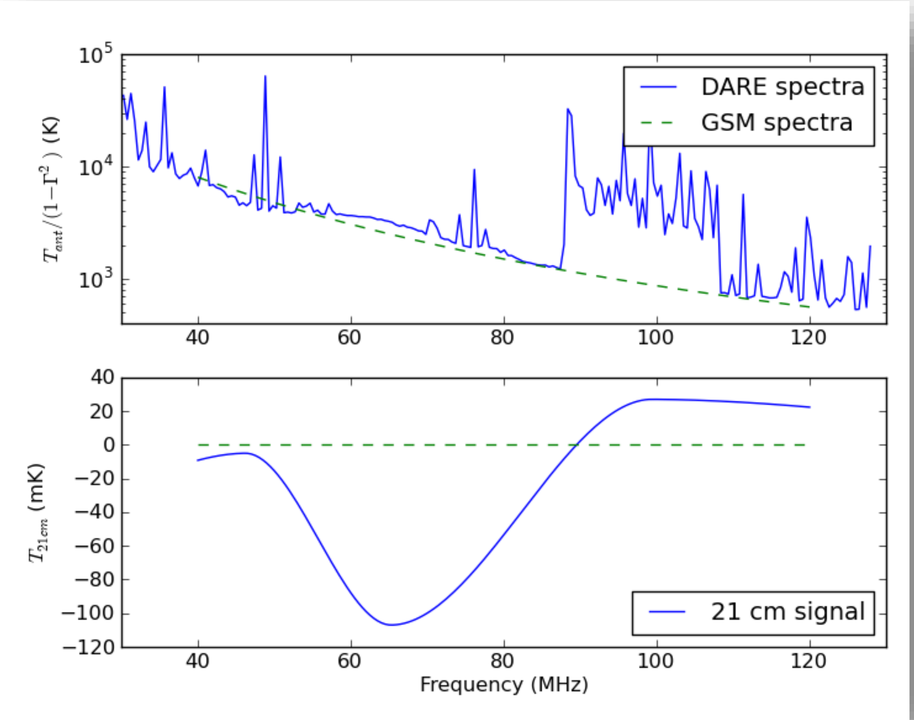
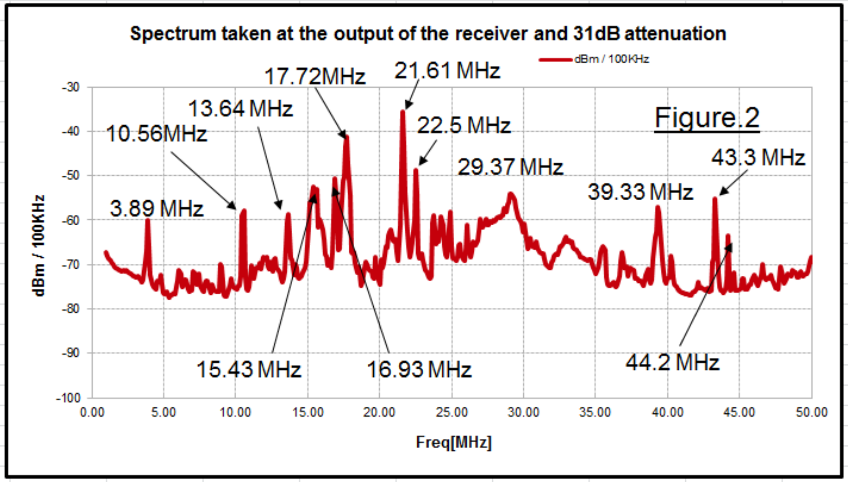
Case for Space: RFI on the Ground as viewed by DARE Prototype



Data collected by DARE engineering prototype in Green Bank, WV. FM band (88-108 MHz) wipes out major portion of low frequency spectrum. Below 60 MHz, effects due to ionosphere become apparent.



Data collected by DARE prototype in Western Australia. Interference spikes are probably due to naval radar. Out-of-band RFI introduces instrumental frequency structure through-out the DARE band.

LOFAR RFI Survey
Offringa et al. 2013, MNRAS, 435, 584.
T (low level RFI) = 3.2 K at 30 -76 MHz.

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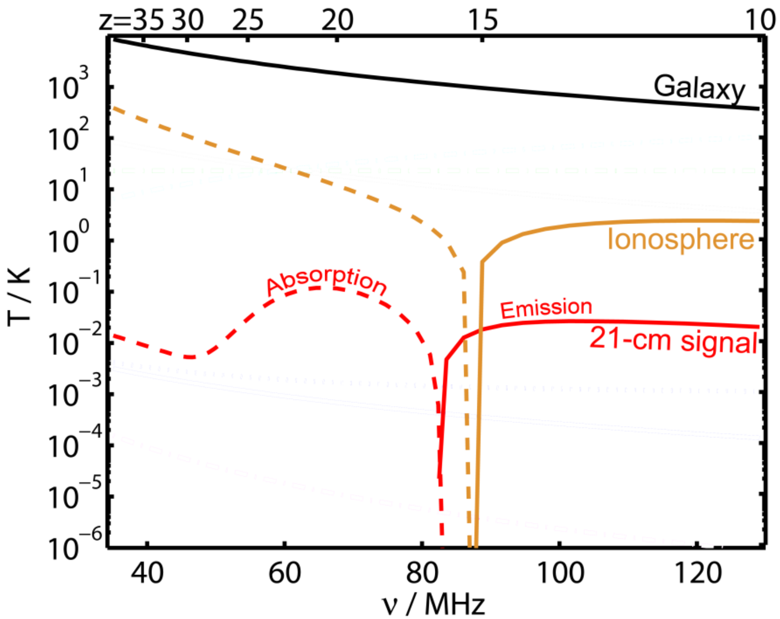
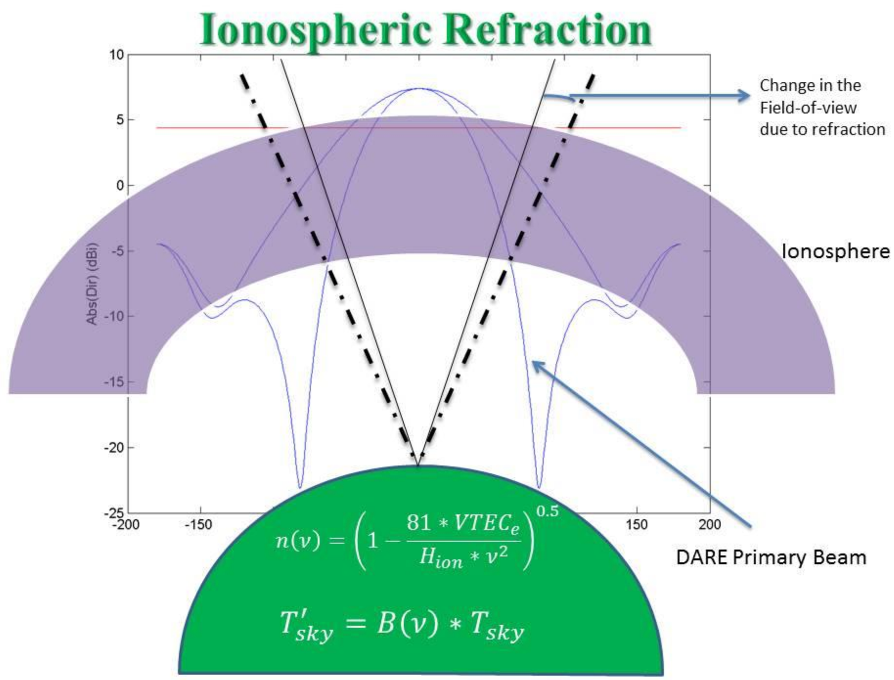
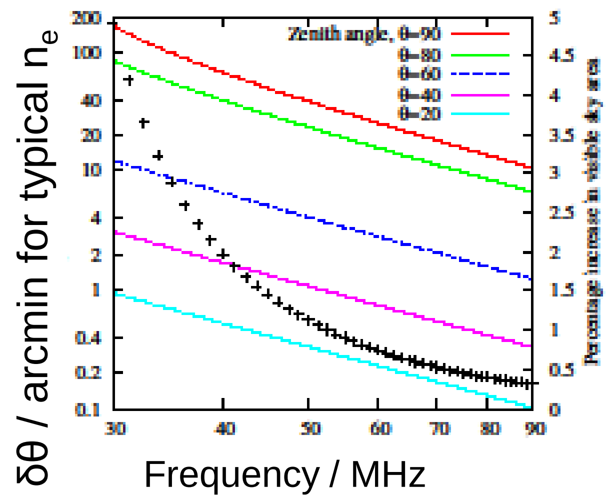
Case for Space: Emission, Absorption, Refraction from the Ionosphere



The ionosphere absorbs at low radio frequencies, while its hot electron population also produces emission. Spectral shape *can mimic our signal* and is *time-variable*.

Ionospheric effects generally go as $\sim\nu^{-2}$





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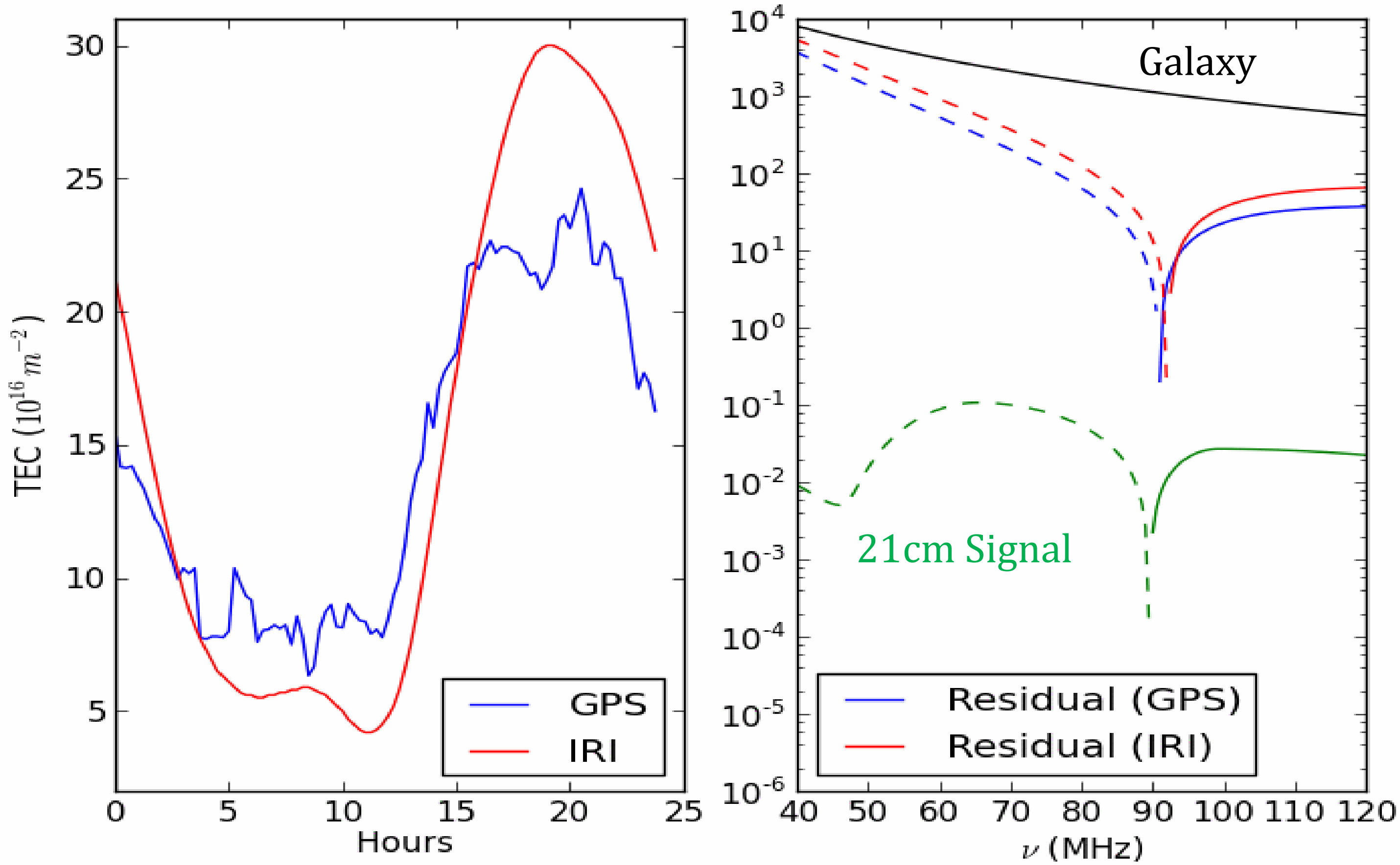
Case for Space: Combined Effects of Refraction and Absorption/Emission from the Ionosphere



GPS data Green Bank (WV) location IRI- International Reference Ionosphere Model

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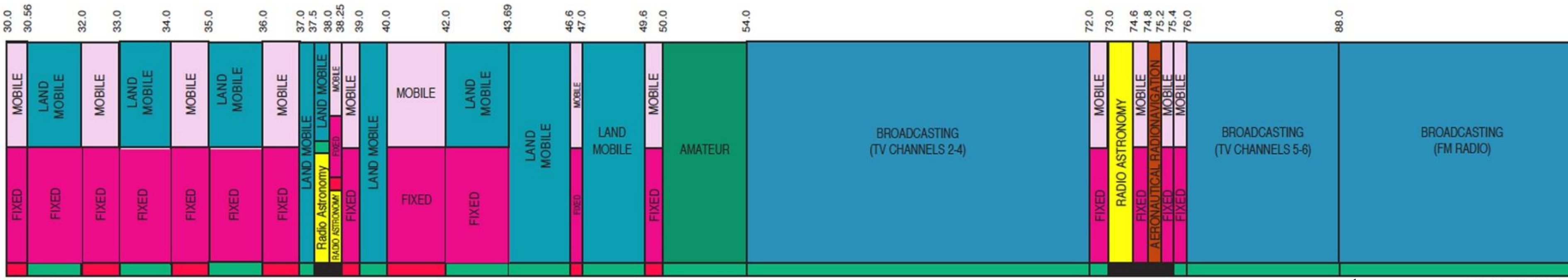
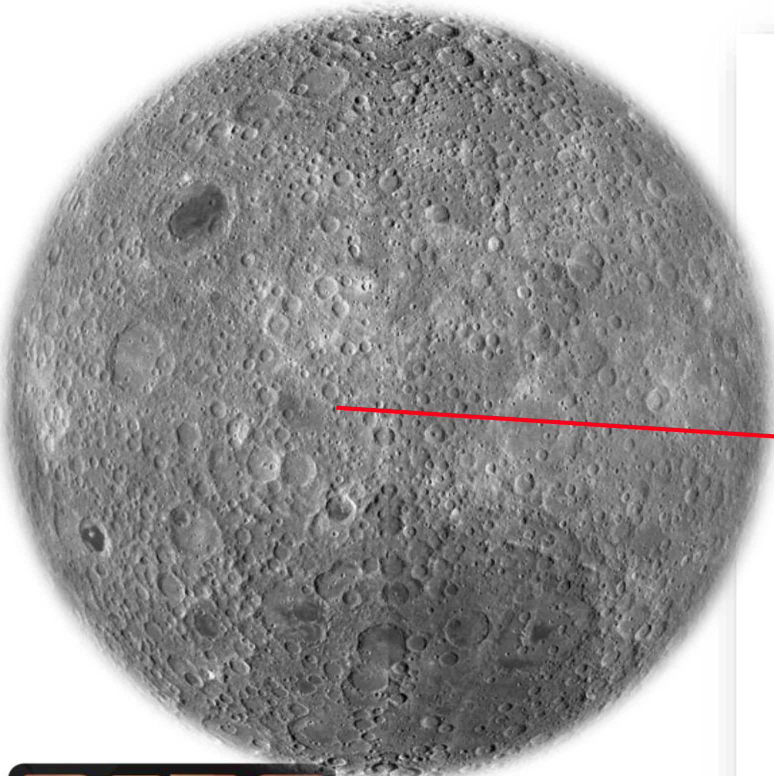
Datta *et al.* 2014, arXiv1409.0513

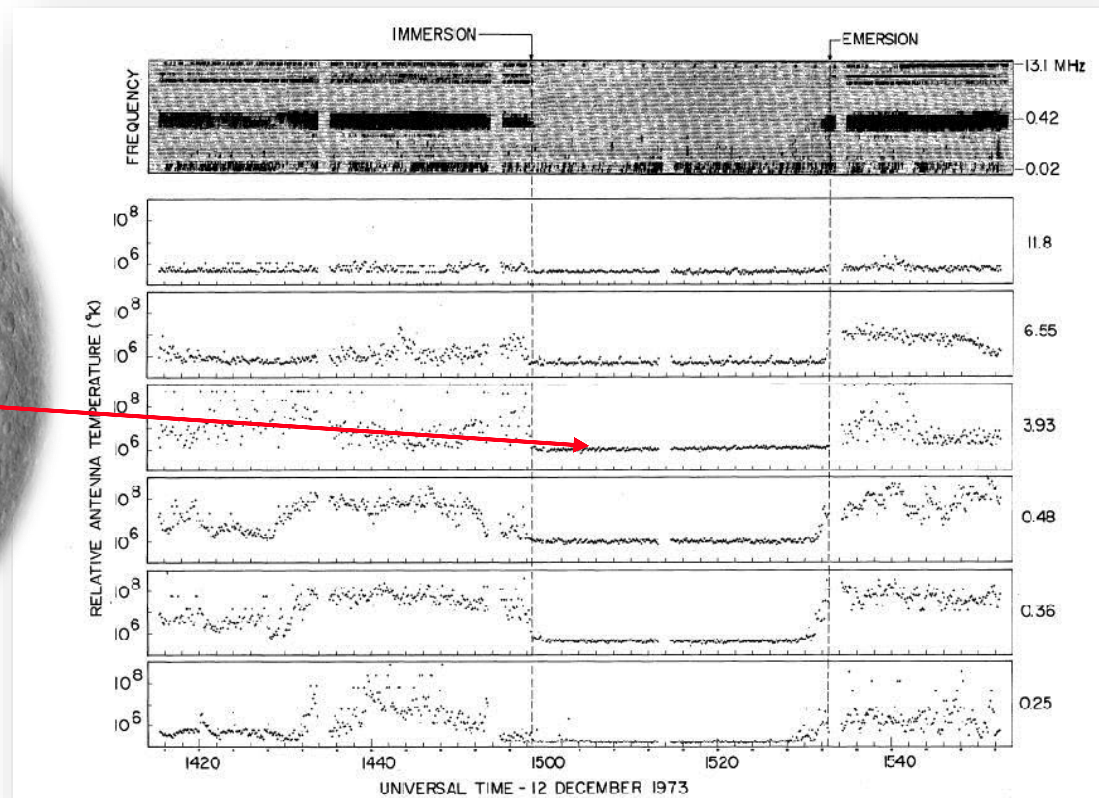
Lunar Farside: No RFI or Ionosphere!



30 MHz **(z=46)** **(z=13)** 100 MHz



RAE-2 1973



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DARE Baseline Mission Concept

Time in radio-quiet, solar eclipse cone	≈1000 hrs over 2 years
Instrument	3-meter length biconnical antennas; correlation receiver; digital spectrometer; operates at 40-120 MHz
Launch Date	Q3/4 2020
Launch Vehicle	Secondary payload on ULA Atlas V
S/C Structure	60-inch ESPA as S/C structure and Faraday cage
Instrument I/F	Stack second ESPA to house instrument
Launch Injection Orbit	GTO
Earth-to-Moon trajectory	Translunar injection with lunar flyby
Propulsion	Regulated monoprop capable of delivering Δv = 2200 m/s (includes: TLI, TCMs, Lunar Targeting, LOI, orbit maintenance)
Lunar Orbit	125 km circular, ≈0° inclination

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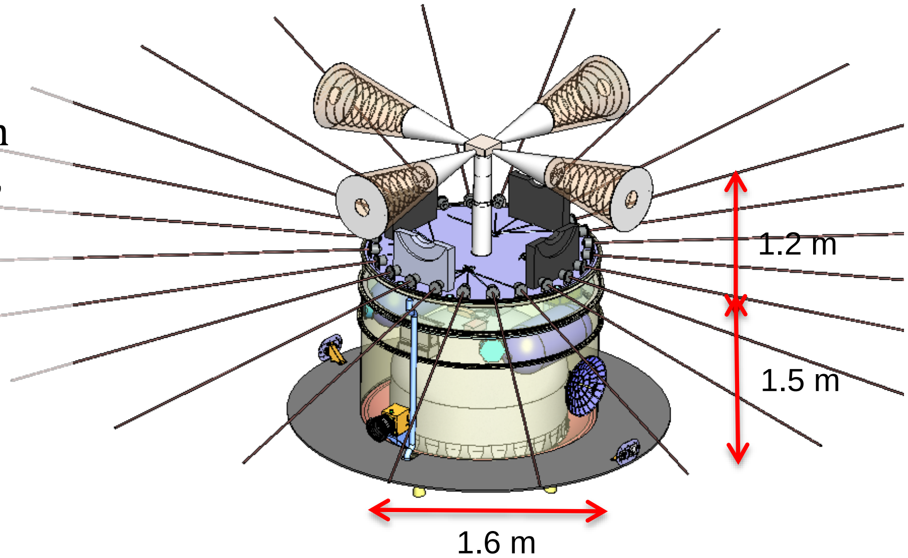
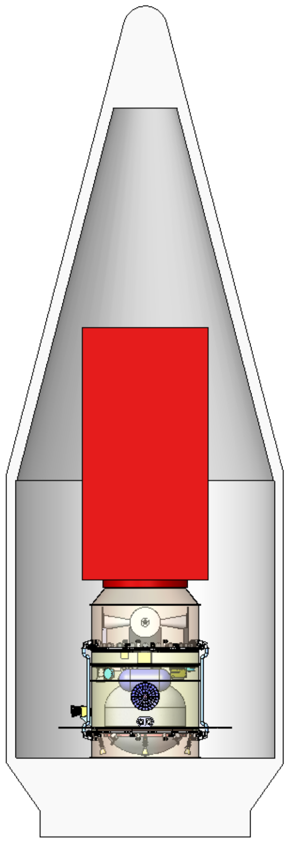
Spacecraft Concept

- **2200 m/s of ΔV**
  - Trans-lunar injection from GTO, lunar orbit insertion, trajectory correction maneuvers, orbit maintenance, momentum management
- **Ability to launch as a secondary on a ULA Atlas V with a 4000 kg primary PL**





DARE in a ATLAS V fairing

DARE performance margins are substantial in all areas

Requirements and Margins	Requirement	Performance	Margin
Observatory Wet Mass	1,600 kg	1,155 kg	38%
Science Data Storage Capacity	1.6 GB	4 GB	150%
Power generation during science	257 Watts	361 W EOL	40%
Pointing Knowledge (3-sigma/per axis)	1 degree	0.028 deg	3471%
Pointing Control (3-sigma/per axis)	1 degree	0.028 deg	3471%
Propellant Load	565 kg	714 kg	21%**
Propellant Tank Capacity	714 kg	959 kg	34%
EMI	100 dB shielding	106 dB shielding	6 dB

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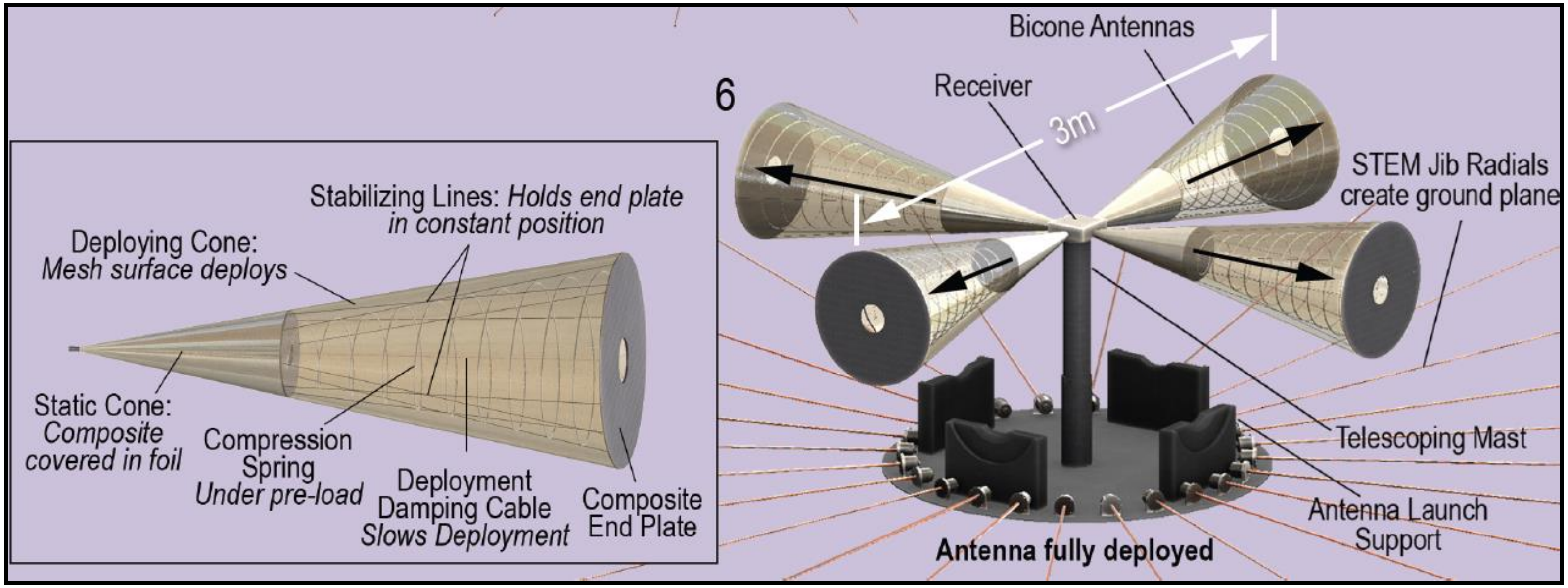
Science Instrument: Baseline Design



Antenna: Dual, deployable bicones to accommodate launch volume

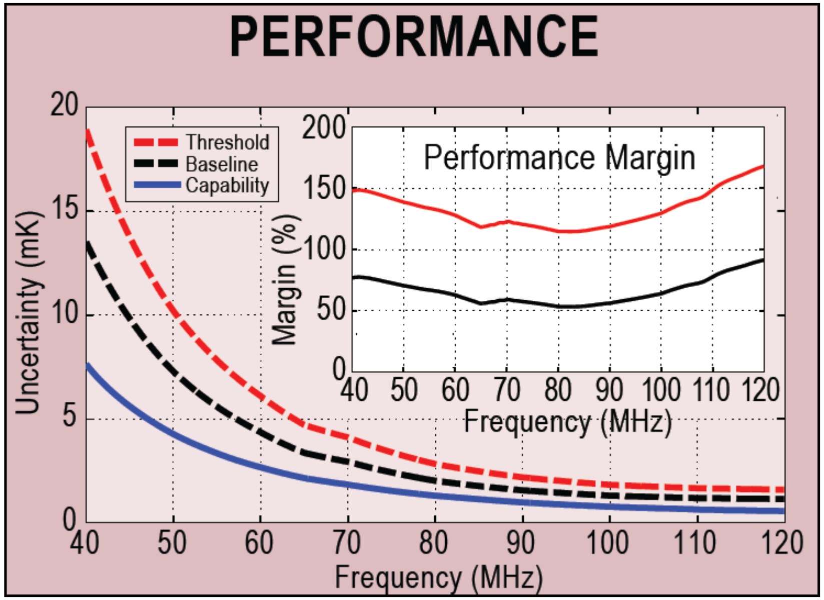
- Mast deploys bicones above S/C deck
- Bicones deploy to achieve length
- Jib Radials deploy to form ground plane

Receiver: Pseudo-correlation Architecture + Reflectometer

- Heritage from WMAP, Planck, Microwave Limb Sounder on UARS.
- Thermally controlled front-end receiver electronics enclosure

Spectrometer

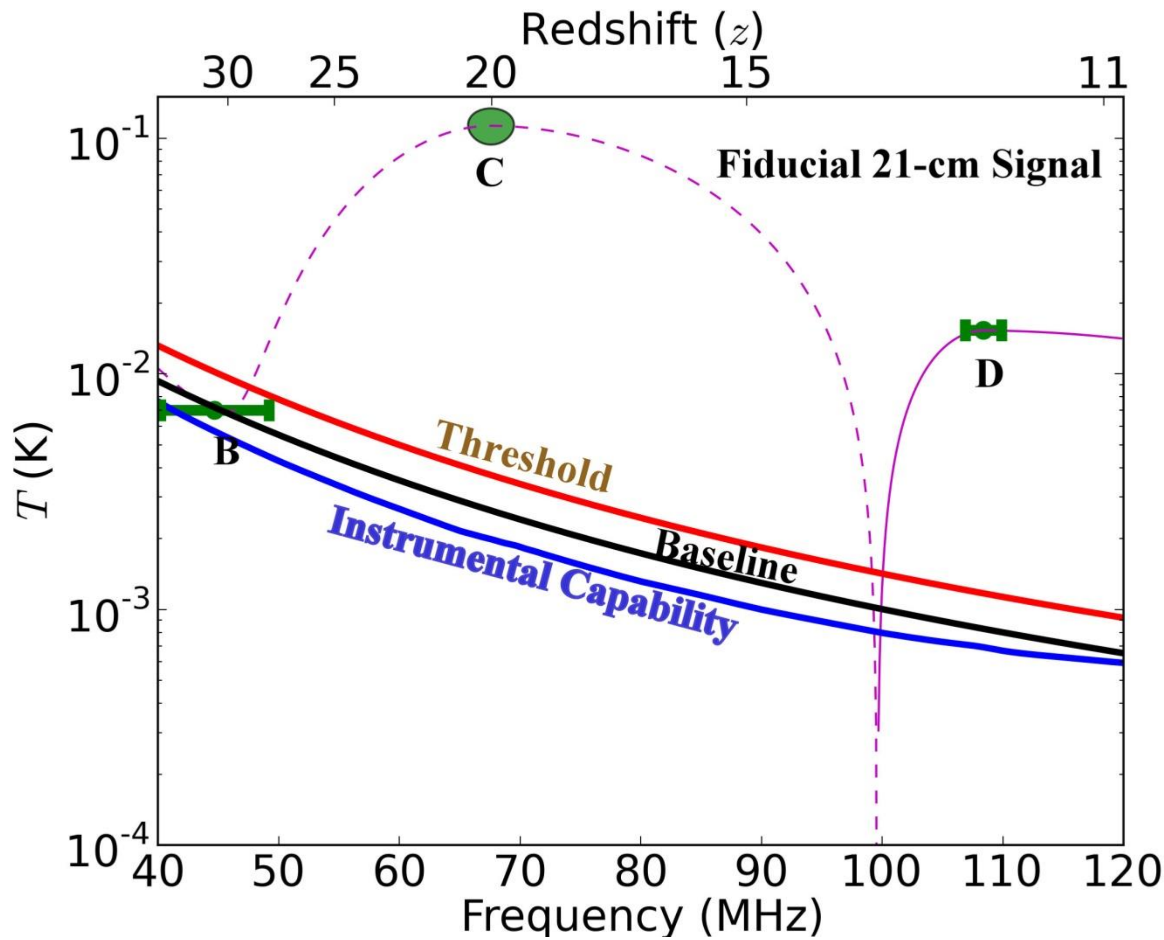
- Achieves 10^6 dynamic range
- Uses space-qualified FPGAs.

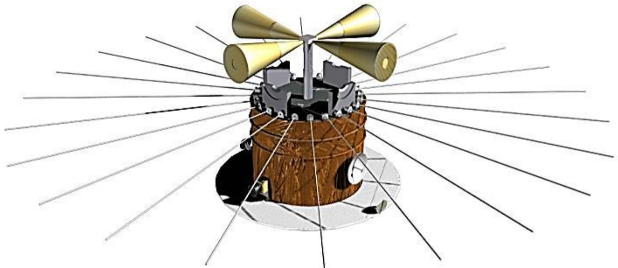


Science Instrument: Sensitivity

The Sensitivity of DARE's radiometer meets the science requirements:

- Precise measurements of Turning Point redshifts:
  - $z_B = 30 \pm 5$
  - $z_C = 20.0 \pm 0.5$
  - $z_D = 12.1 \pm 0.2$
- Measurement of T_C = -114±20 mK.





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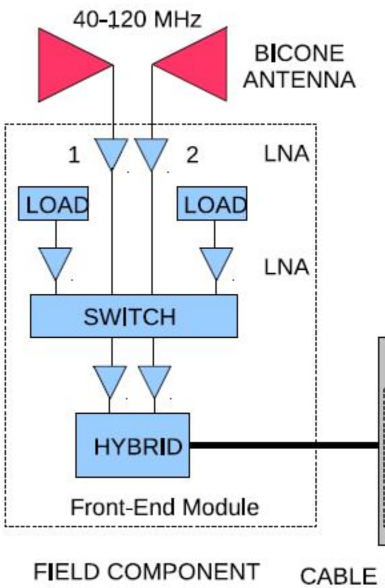
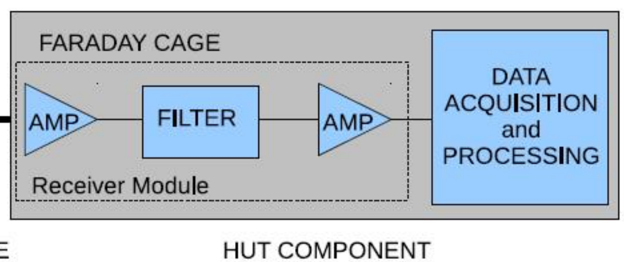
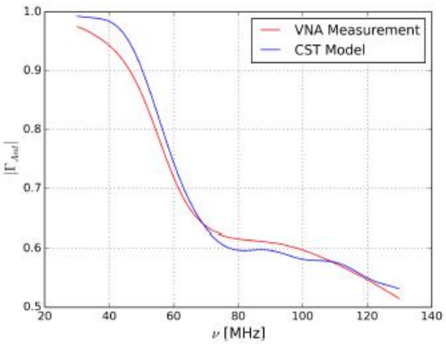
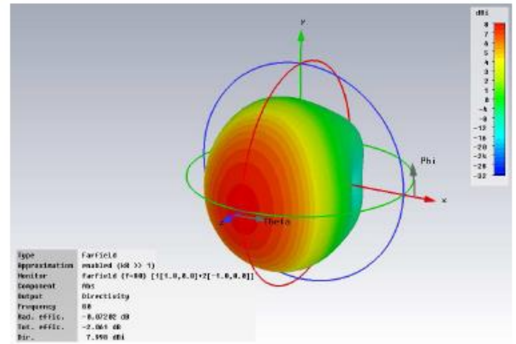
DARE Engineering Prototype:
Cosmic Twilight Pathfinder

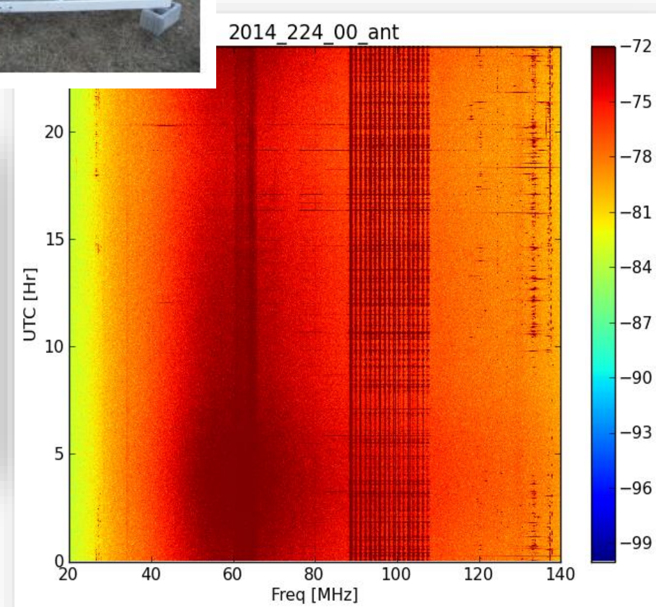


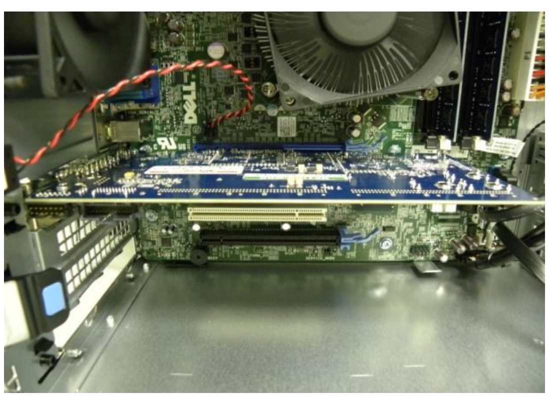




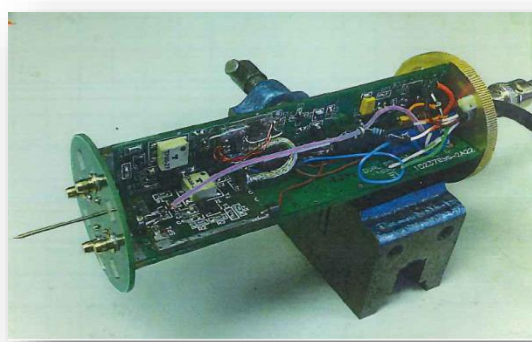


Low Noise Amplifier (LNA)





Data Acquisition System

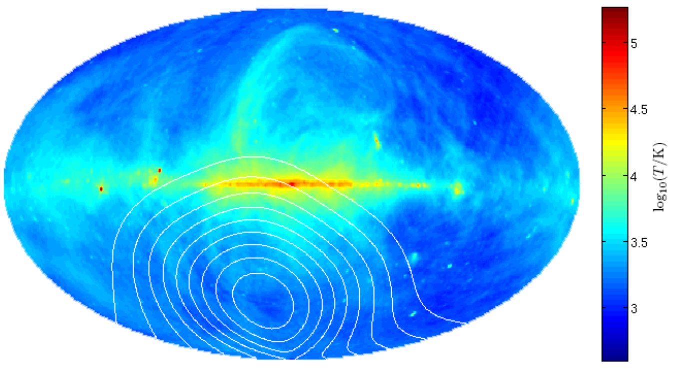


Balun - PAPER Heritage

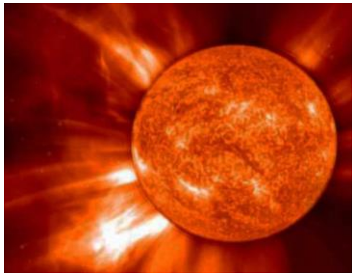
Bradley, Nhan, Datta & Burns

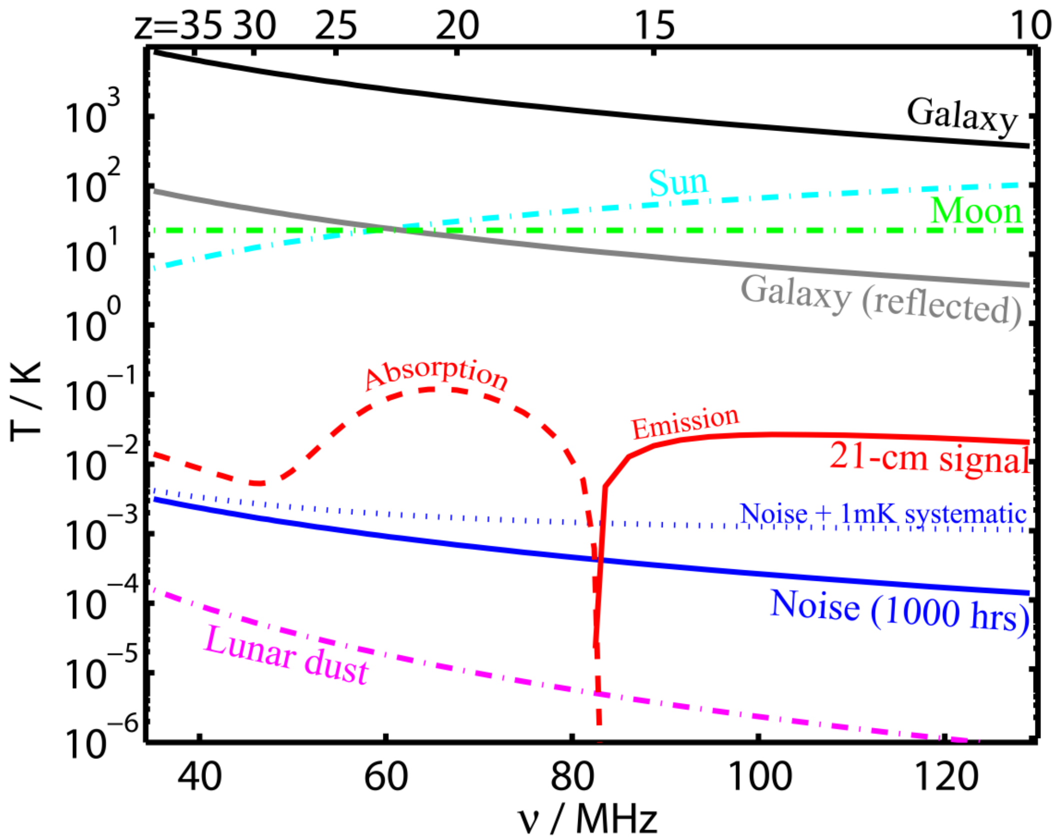
DARE’s Biggest Challenge: Foregrounds

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



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





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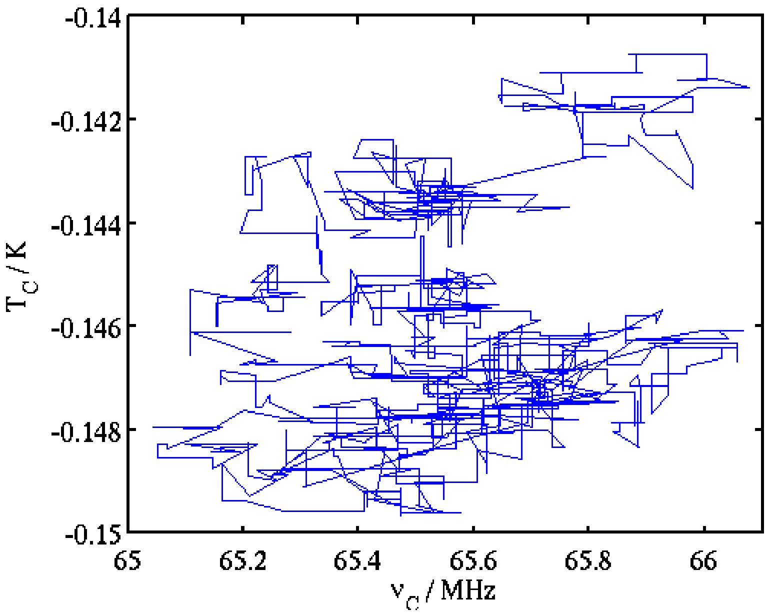
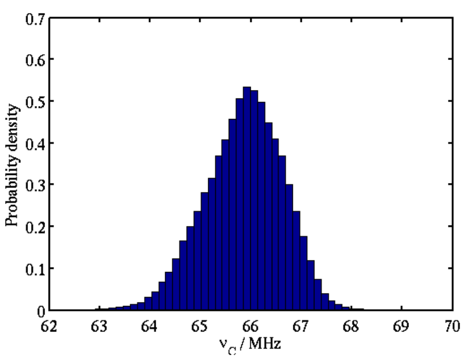
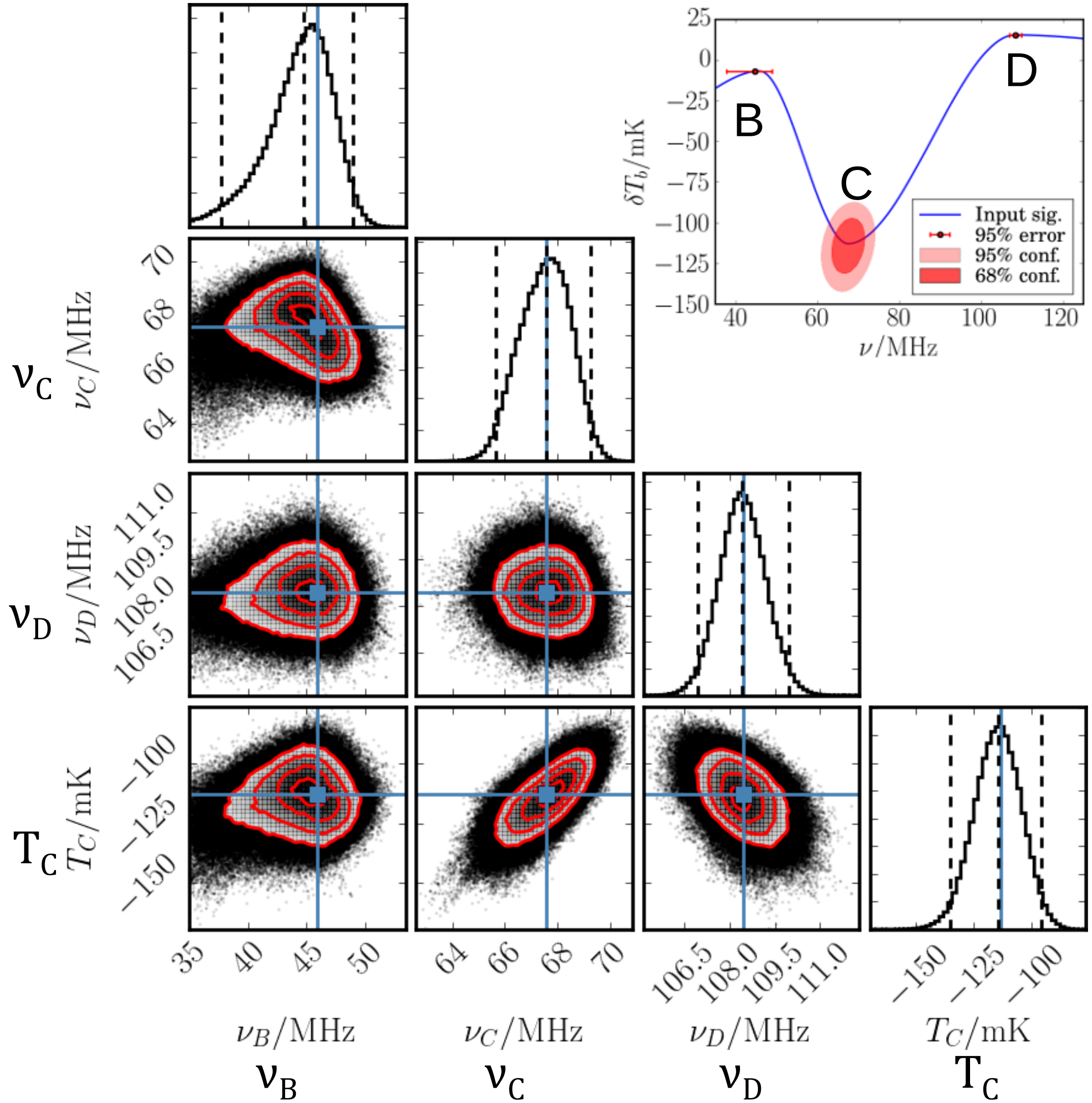
Signal Extraction using MCMC (affine-invariant)





Random walk through parameter space → unbiased, random samples of the posterior probability distribution



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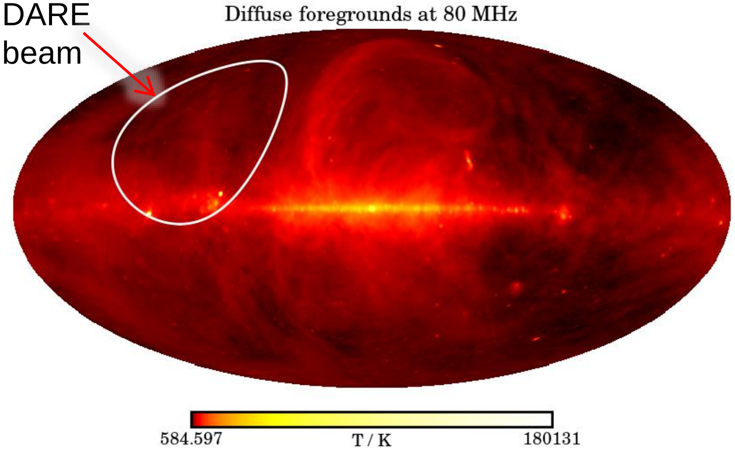
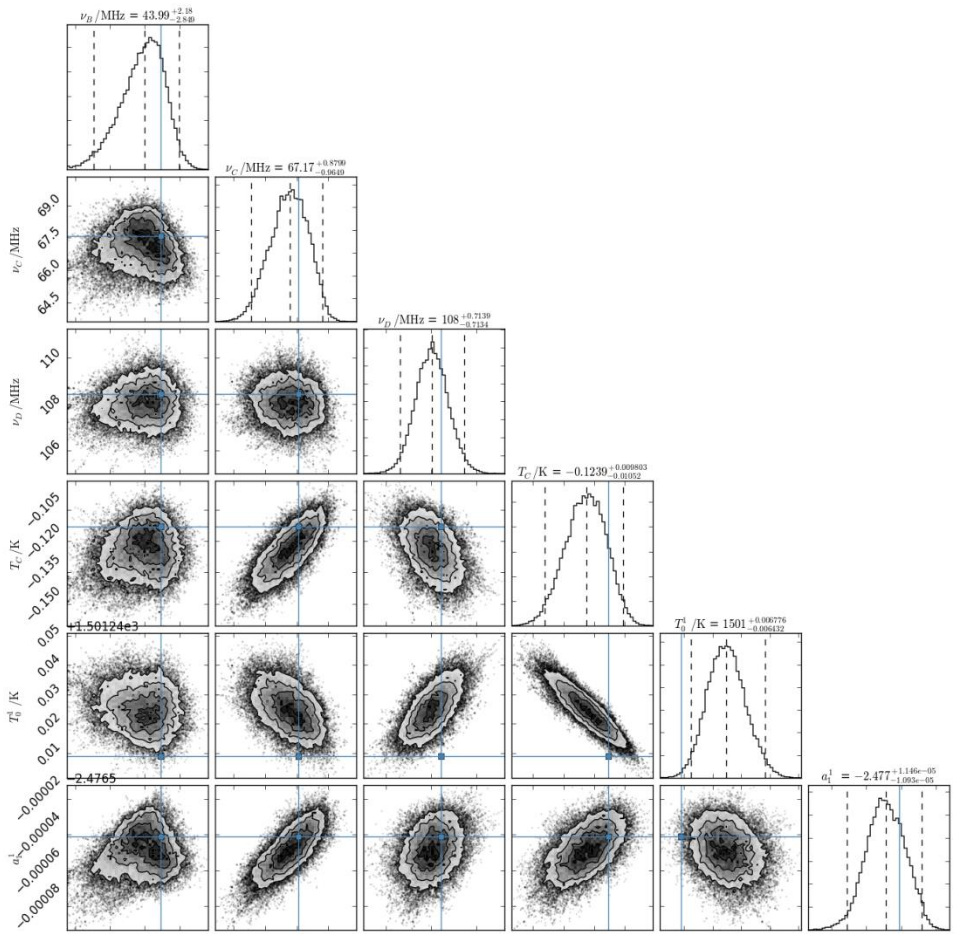
For details see Harker et al. (2012), MNRAS, 419, 1070

Galactic Foreground





- Nonthermal + free-free radiation theoretically produces smooth spectrum when averaged along line-of-sight (e.g., Petrovic & Oh, 2011).
- From 100-200 MHz, EDGES does NOT find foreground spectral structure at levels >10 mK over 10 MHz spectral scales (Bowman & Rogers, 2010).
- 21-cm signal is uniform spatially but with prominent frequency structure. Contrast against foreground that varies spatially but with simple spectrum => clean separation of signal from foreground with 8 DARE sky fields.

Test: Non-smooth, 10 mK foreground component added in blind test. Produced offset in foreground parameters but fit to Turning Points within 95% confidence.

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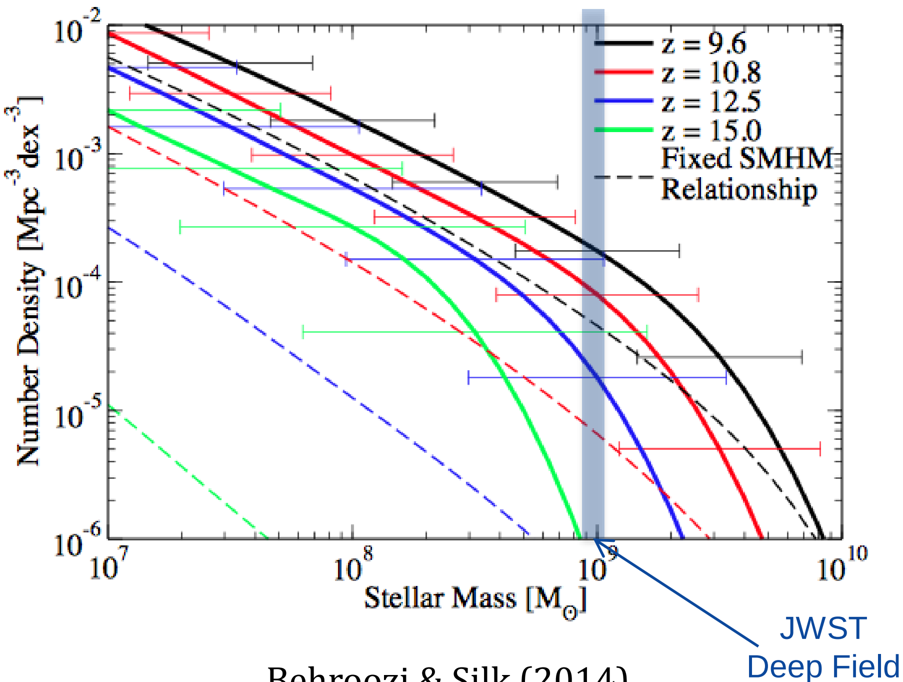
Synergies: Major Instruments

- **Planck recently released their full dataset**
  - Limit on reionization, nothing about pre-reionization
- **Hydrogen Epoch of Reionization Array (HERA, PAPER, MWA, LOFAR, etc.)**
  - HERA is a next-generation ground-based 21-cm interferometer (Parsons et al.).
  - Should nail down middle/late parts of reionization history
  - *May* poke into pre-reionization era
- **LEDA, LWA, others may go after very high-redshift signal (but ionosphere…)**
- **James Webb Space Telescope**
  - DARE will have comparable timescale
  - Images (bright) galaxies out to (optimistically) z~15
- **Athena**
  - X-ray probe of black holes/AGNs to z~10.



Behroozi & Silk (2014)

DARK AGES RADIO EXPLORER

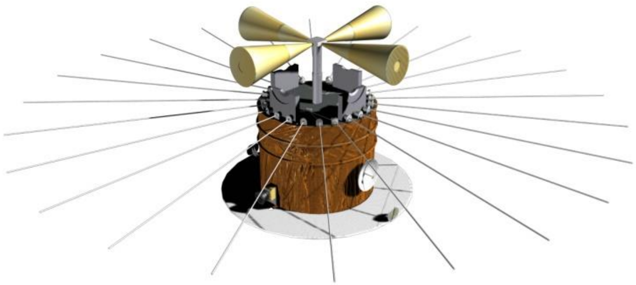
Dark Ages Radio Explorer (DARE)

DARE is designed to address:

- When did the First Stars ignite? What were these First Stars?
- When did the first accreting Black Holes turn on? What was the characteristic mass?
- When did Reionization begin?
- What surprises emerged from the Dark Ages?

DARE will accomplish this by:

- Constructing first sky-averaged spectrum of redshifted 21-cm signal at $11<z<35$.
- Flying spacecraft in lunar orbit & collecting data above lunar farside -- only proven radio-quiet, ionosphere-free zone in inner solar system.
- Using biconical dipole antennas with smooth response function & Markov Chain Monte Carlo method to extract spectral *turning points* in the presence of bright foregrounds.
- Using high heritage spacecraft bus & technologies/techniques from DARE engineering prototype.
- DARE was submitted to NASA as a SMEX proposal in December 2014.



Burns *et al.*, 2012, *Advances in Space Research*, 49, 433.
http://lunar.colorado.edu/dare/