DARE

DARK AGES RADIO EXPLORER

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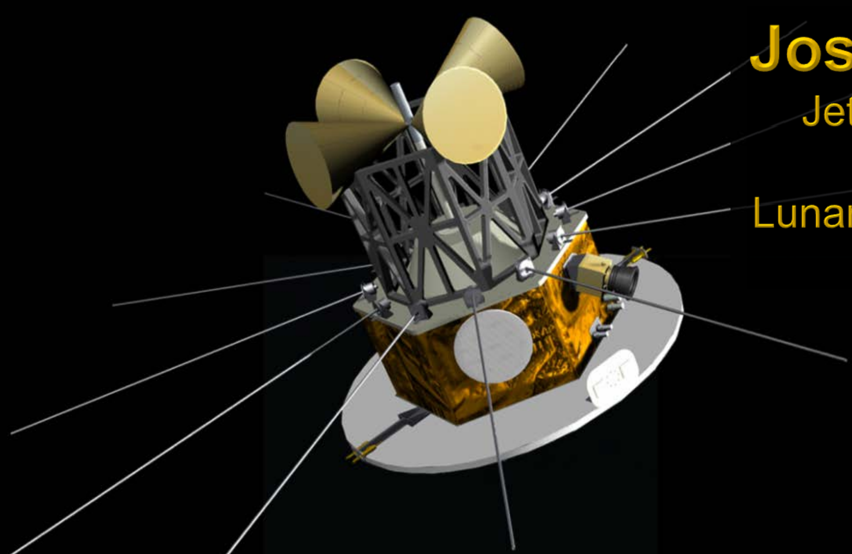

DARE
DARK AGES RADIO EXPLORER

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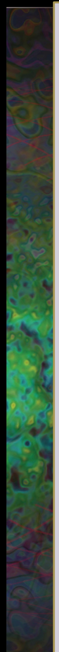
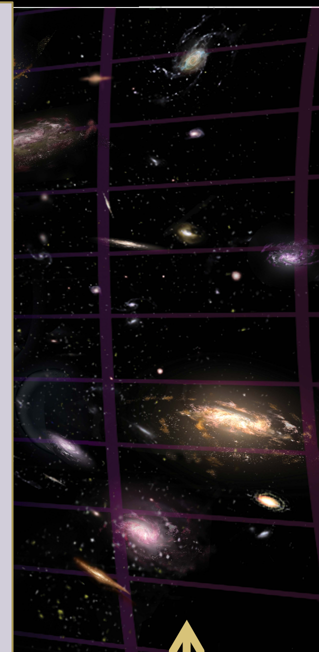
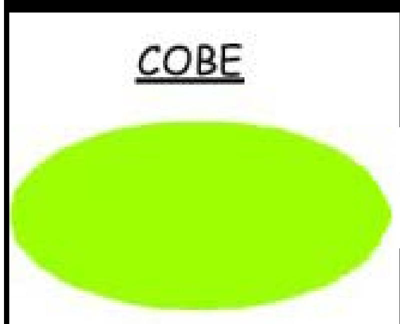
A Brief History of the Universe







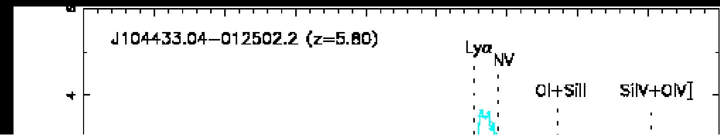
Universe starts in a uniform, largely neutral state

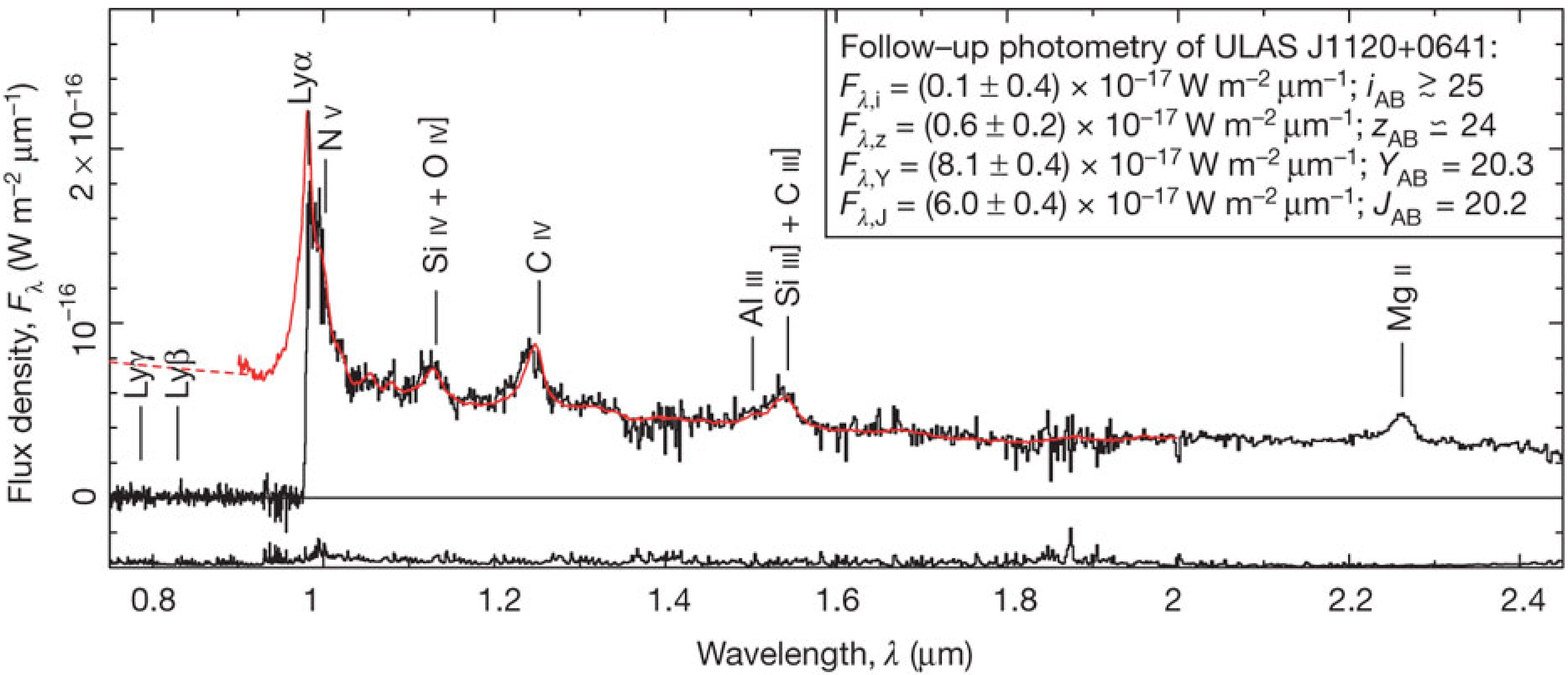
Today, highly structure and ionized.

- What happened?

Epoch of Reionization

Gunn-Peterson trough in high-z

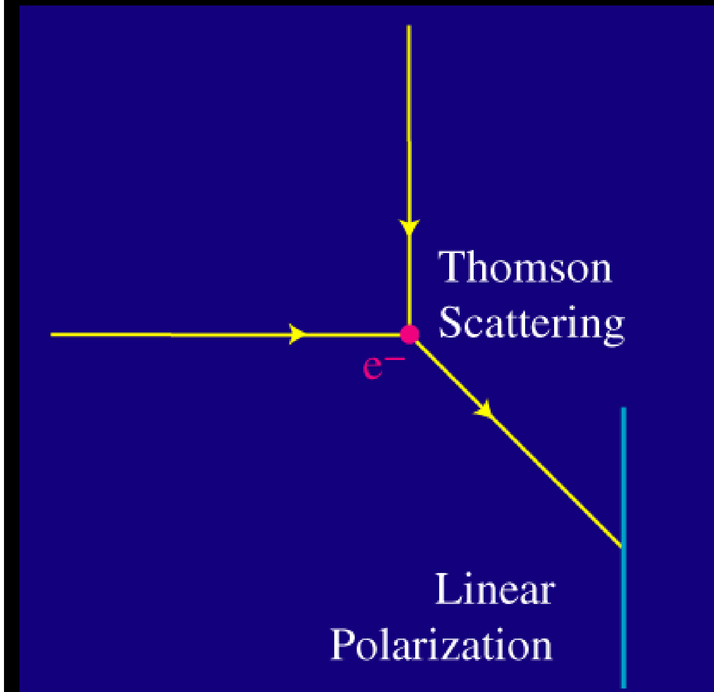




Mortlock et al. 2012

Becker et al. (2001)

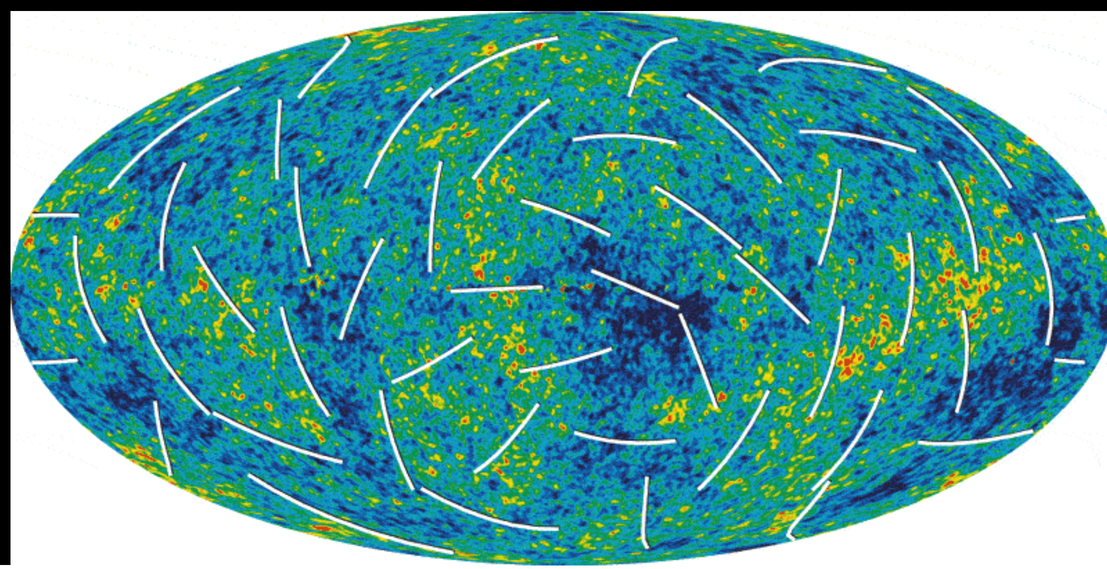
Epoch of Reionization



W. Hu

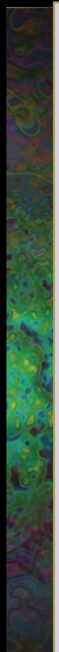
Electron scattering opacity in CMB

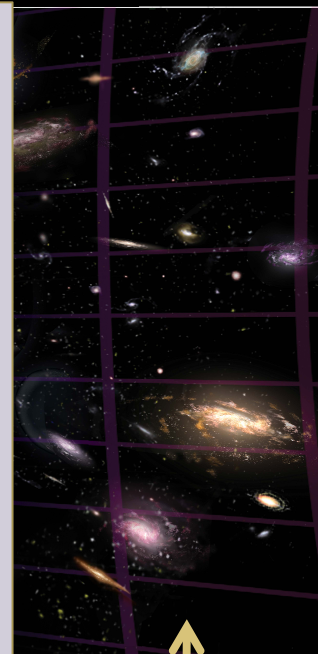
- Thompson scattering induces polarization
- Constrain *integrated* electron density
- $z_{ion} = 10.8 \pm 1.4$

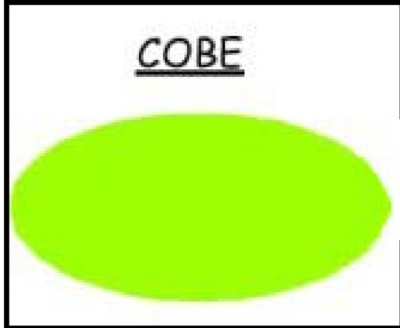


WMAP polarization

A Brief History of the Universe





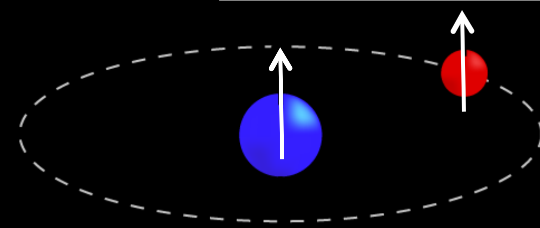


Universe starts in a uniform, largely neutral state

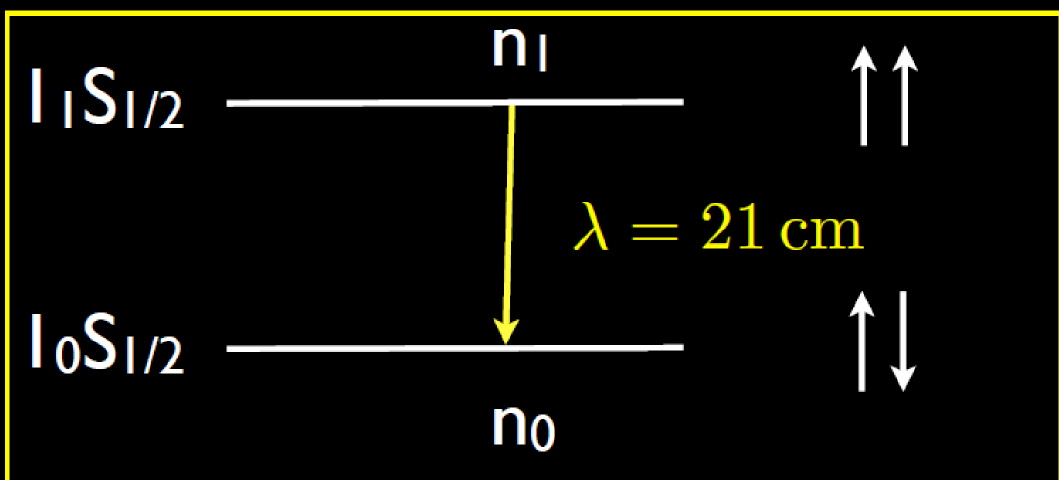
Today, highly structure and ionized.

21-cm Hyperfine Line of Neutral Hydrogen

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



Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

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

Useful numbers:

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

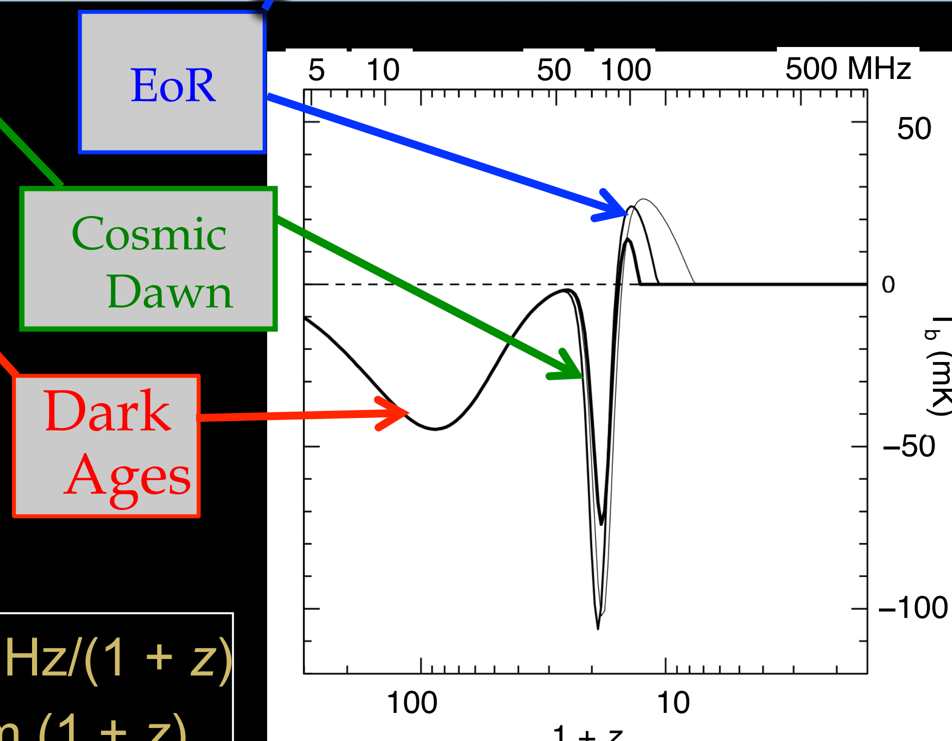
$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$

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

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

Courtesy of J. Pritchard

Hydrogen Signal from EoR and Before

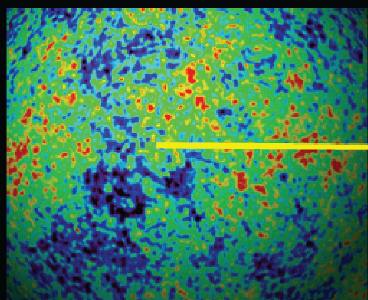


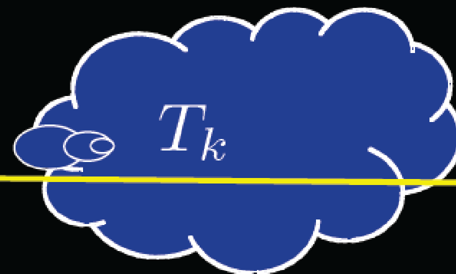
Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

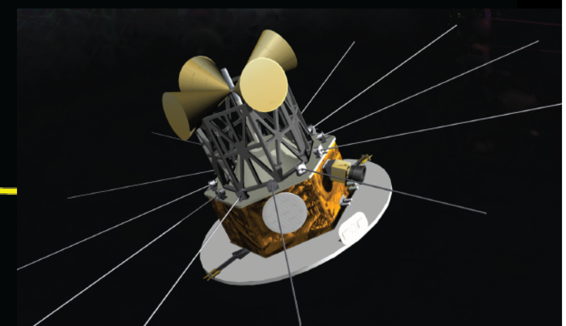
$$\nu = 1420 \text{ MHz}/(1 + z)$$
$$\lambda = 21 \text{ cm } (1 + z)$$

21 cm Cosmology

T_γ T_S T_b







$z = 13$
$\nu = 1.4\,\mathrm{GHz}$

$z = 0$
$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

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

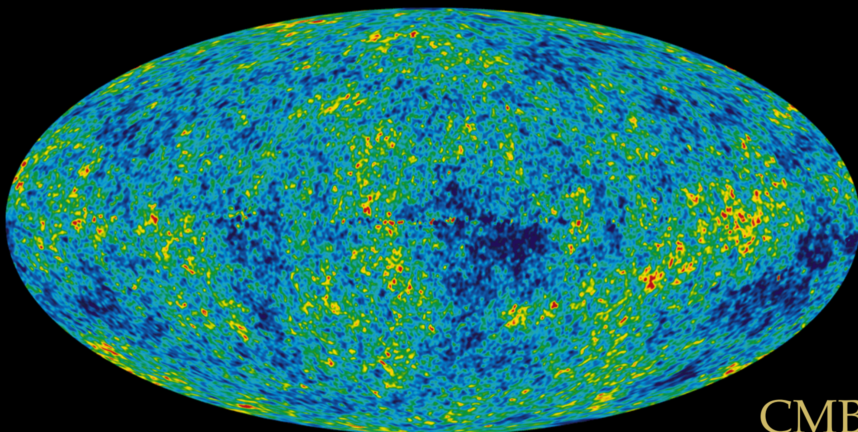
$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\ \mathrm{mK}$$

spin temperature set by different mechanisms:

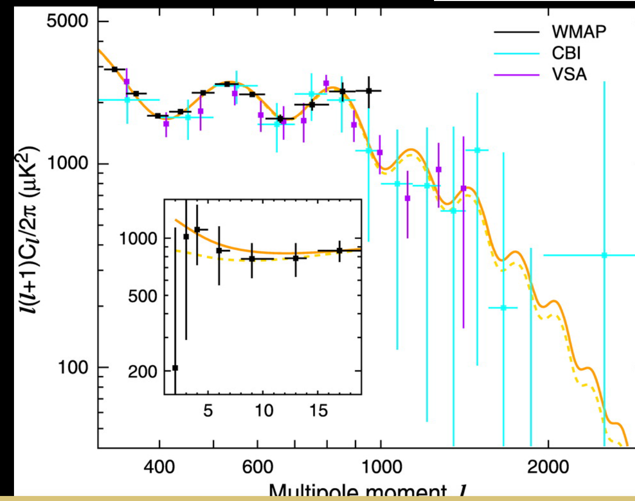
- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect

Courtesy of J. Pritchard

H I Imaging and Power Spectra

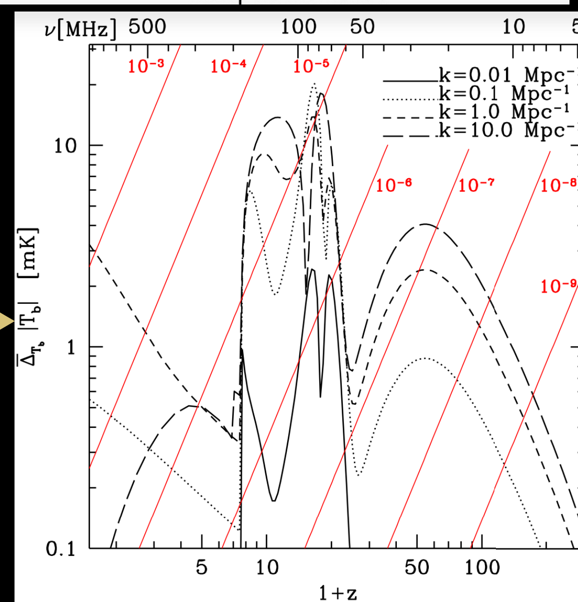


CMB

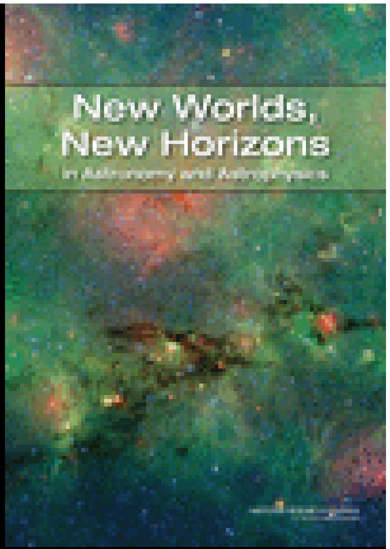


Alvarez et al.

H I power spectrum



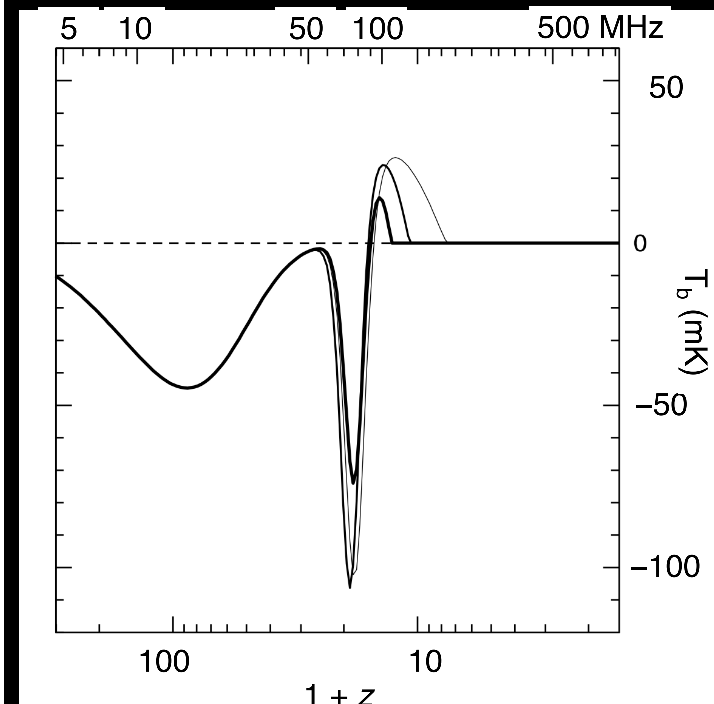
Cosmic Dawn as a Science Objective: Searching for the First Stars, Galaxies & Black Holes

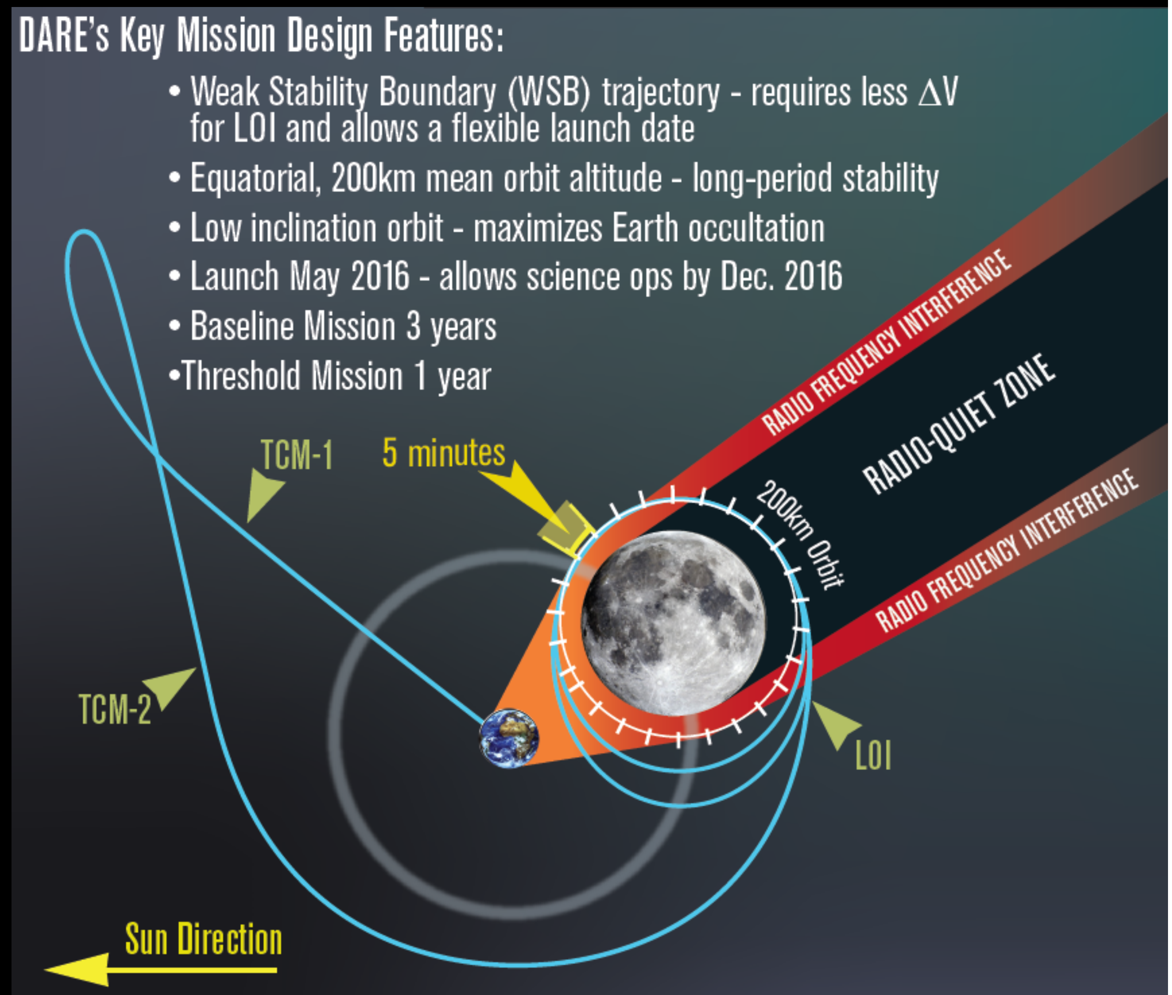


"A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization… Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings."

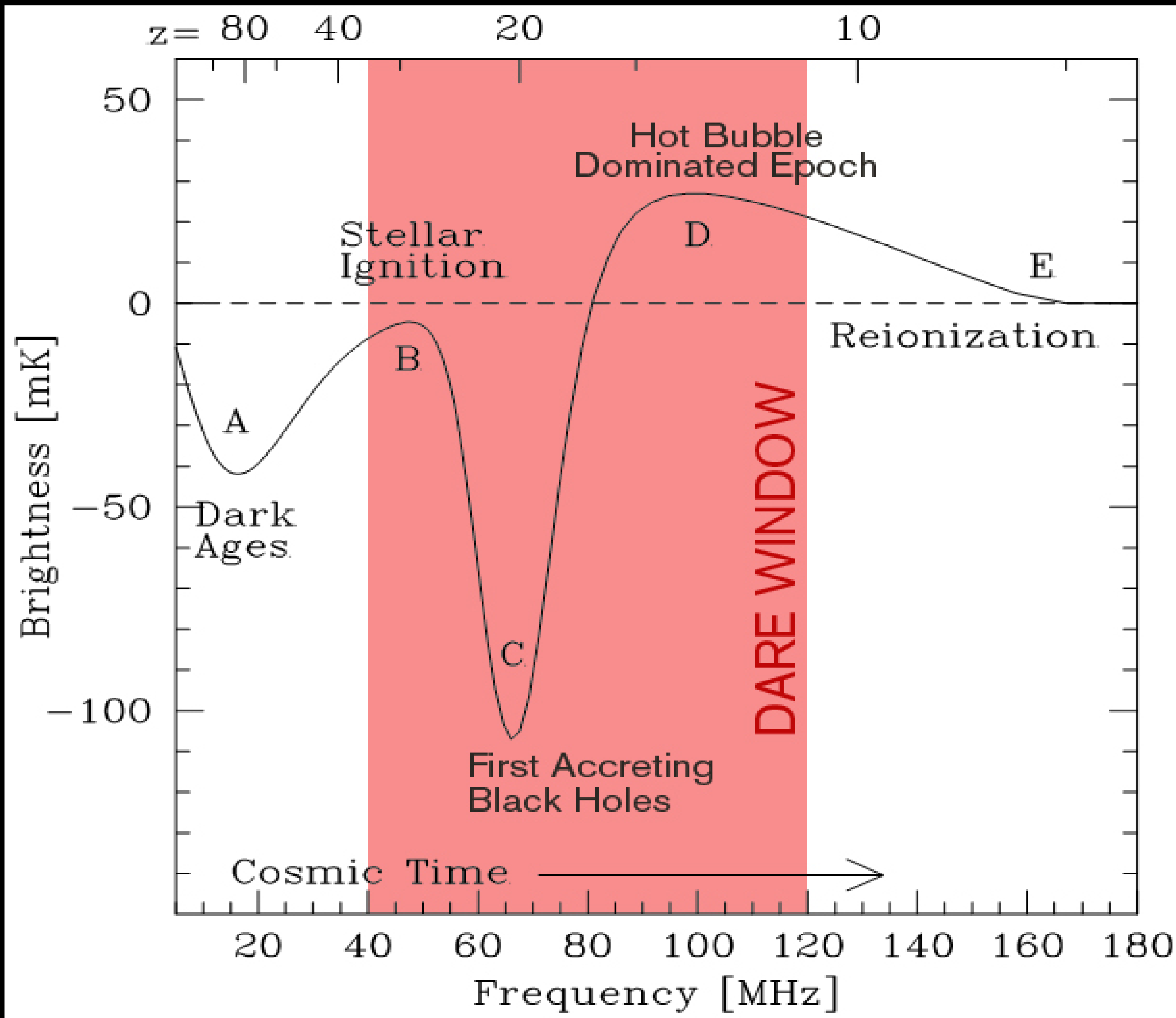
"What were the first objects to light up the Universe and when did they do?" We can uniquely address this mystery with DARE in lunar orbit (sky-averaged 21-cm spectrum) .

Dark Ages Radio Explorer





Prime Science Mission

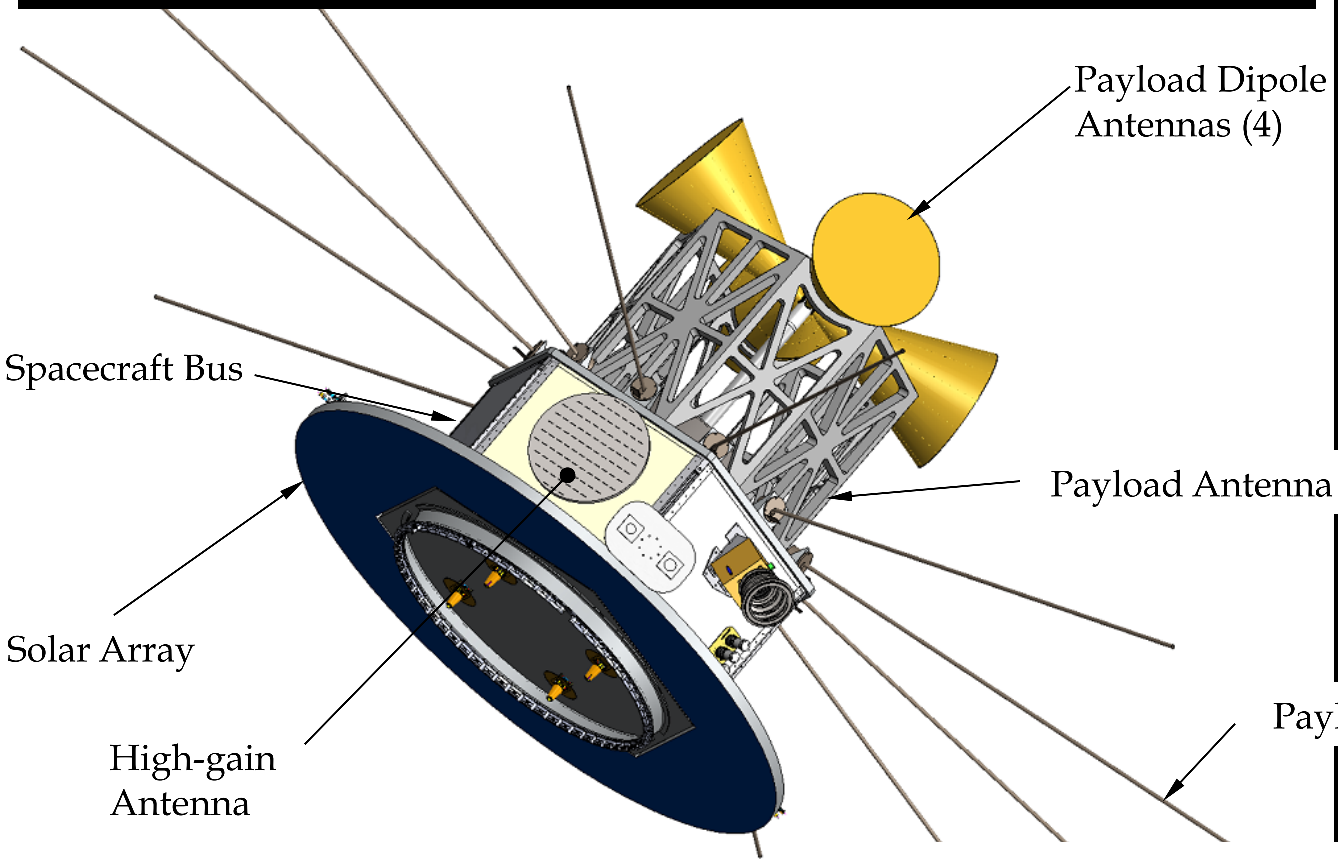


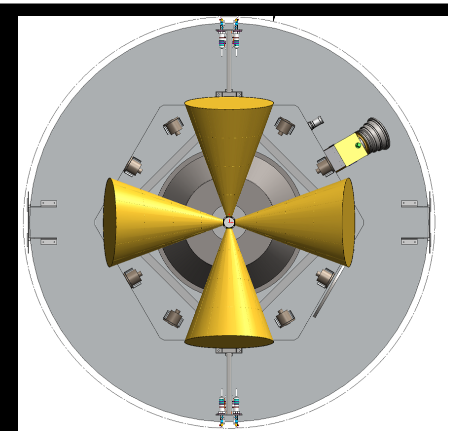
Turning Points B, C, and D

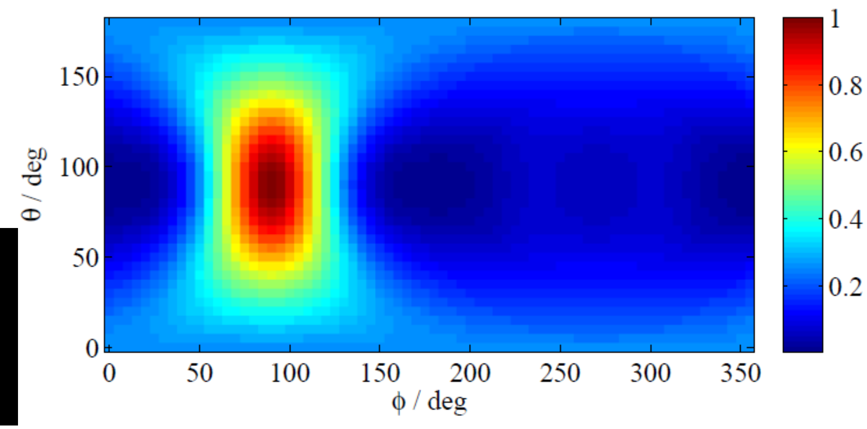
- Measure or constrain their frequencies and amplitudes

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

DARE Spacecraft

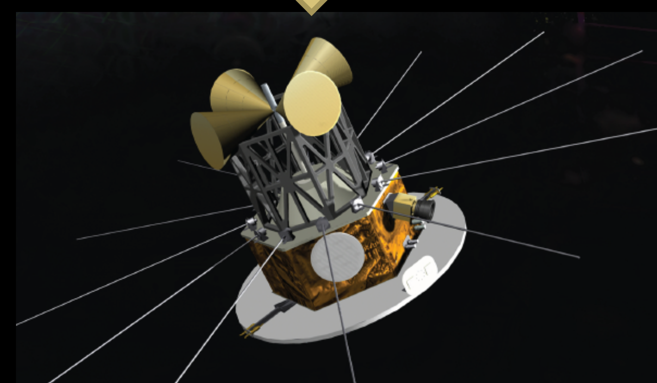






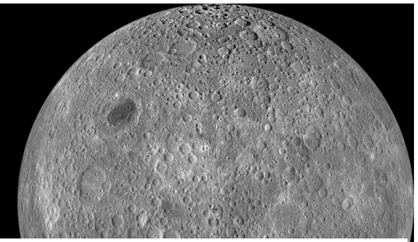
Lessons from EDGES

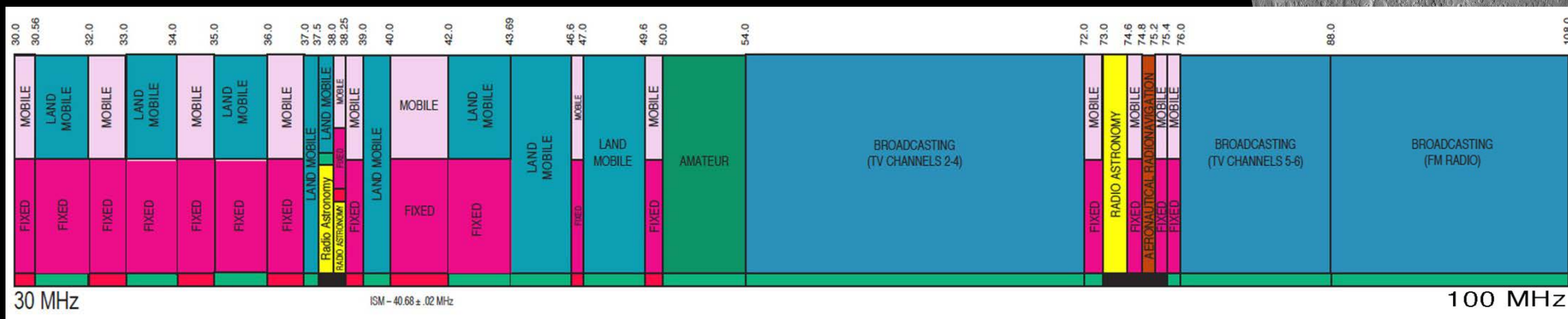
- $10^{9\text{-}10}$ dynamic range difficult because of RFI =>A/D converters need high bit-depths & be highly linear. Susceptible to internal clock stability errors & digital noise.
- Multipath reflections=> complex spectral interference.
- Complex environment makes transferring instrument response function from lab impossible.
- Ionosphere adds significant noise at <80 MHz.



Analogous to why COBE went to space!

Radio Spectrum





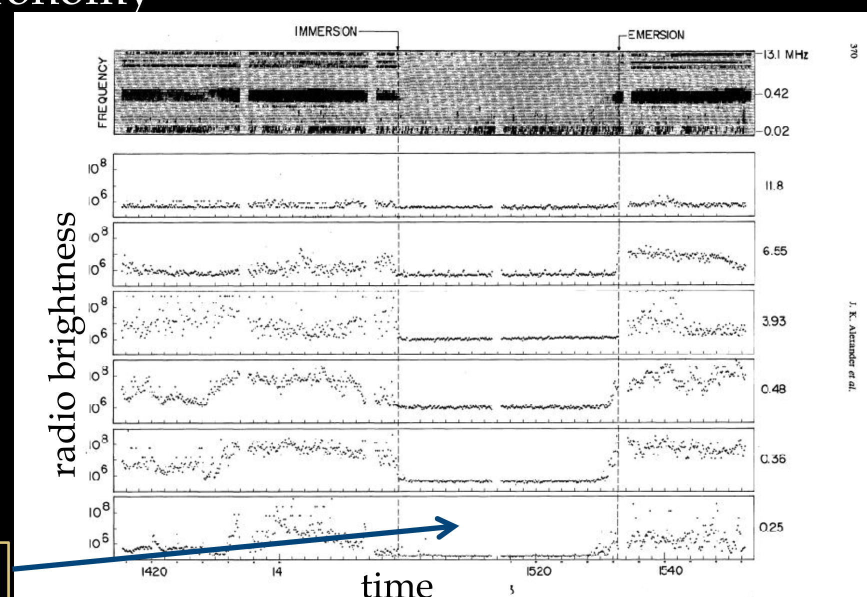
50 Myr since Big Bang

Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages

330 Myr since Big Bang

- Yellow = reserved for radio astronomy

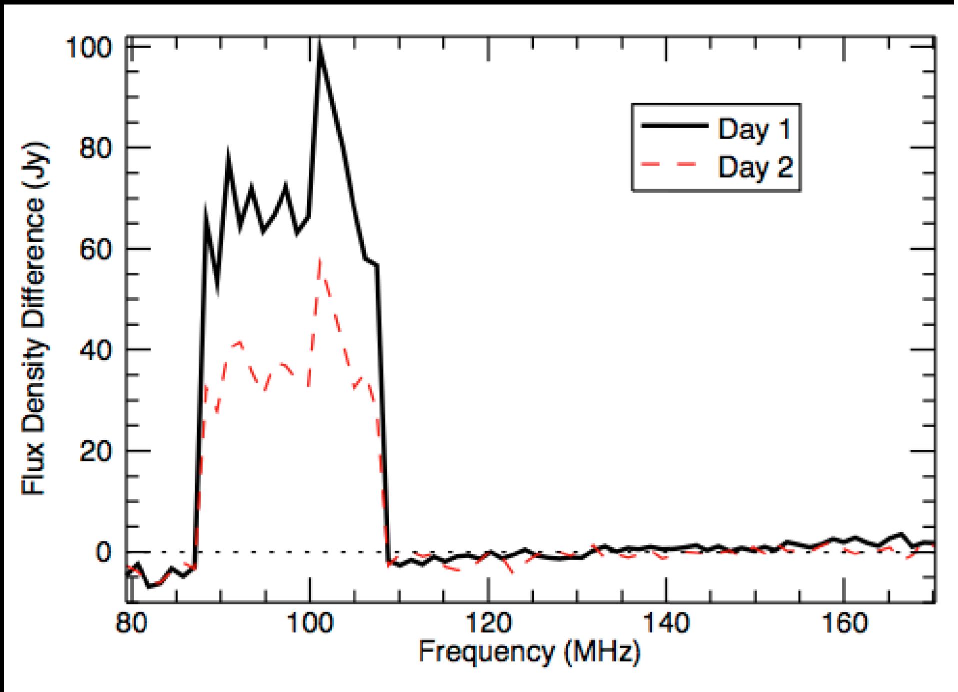
- Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions
- *Apollo* command modules lost communications when behind the Moon.



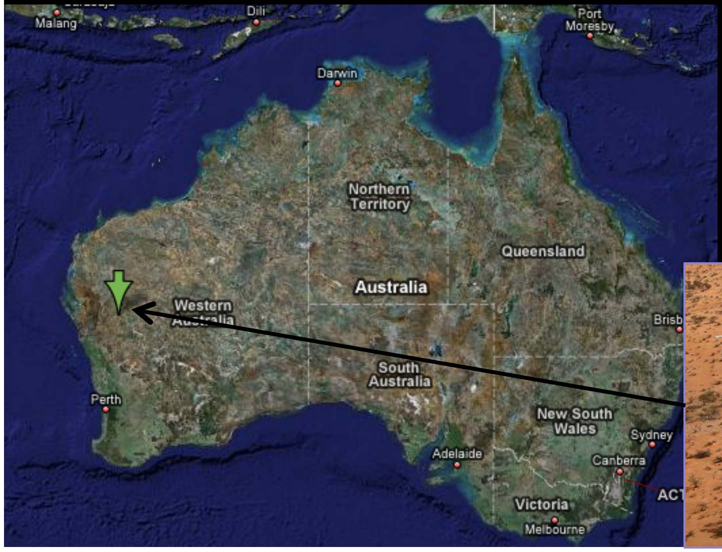
Radio Frequency Interference

Moon reflects Earth's RFI!

Satellites visible, too ....

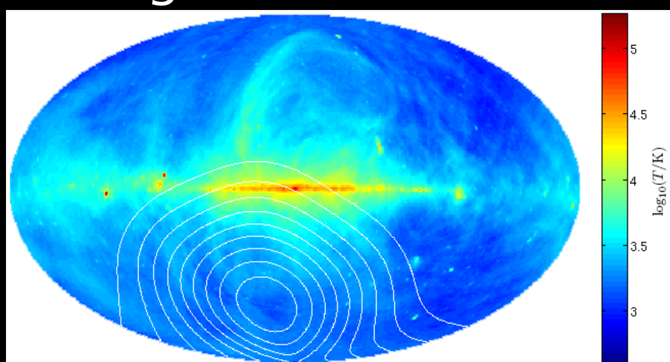


Spectrum of Moon from MWA

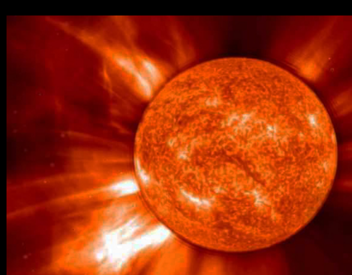


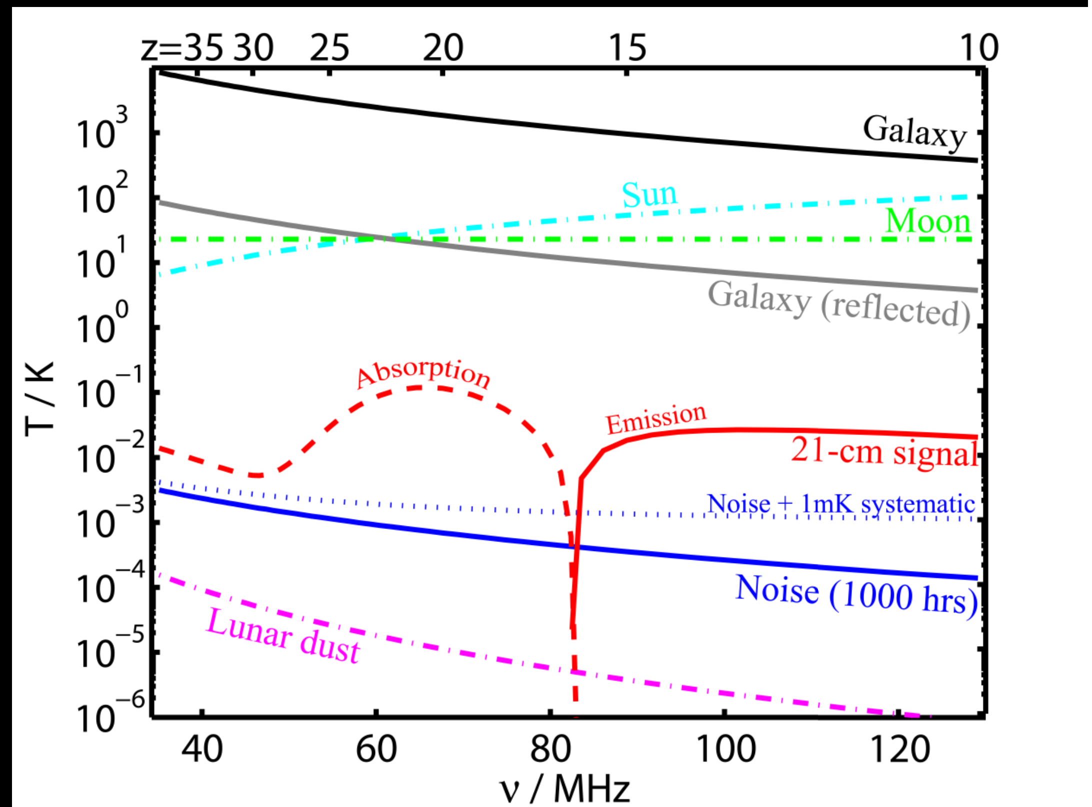
DARE's Biggest Challenge: *Foregrounds*

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

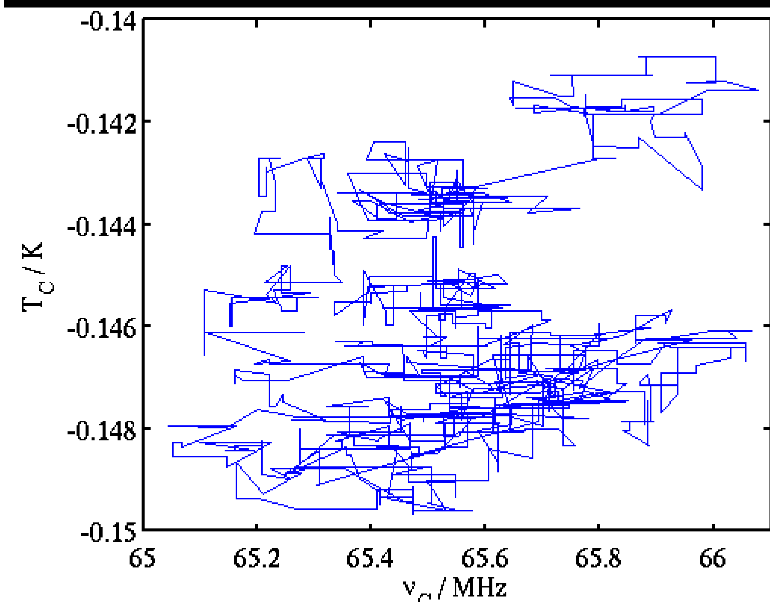


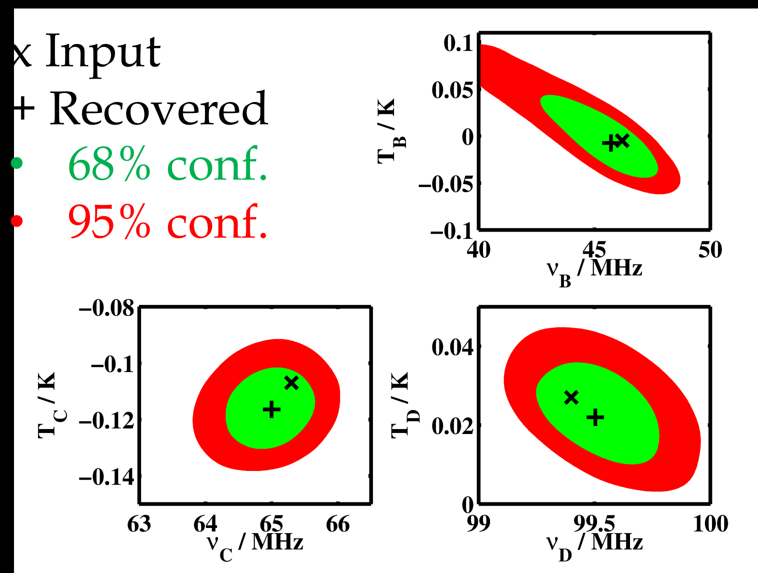
2) Solar system objects: Sun, Jupiter, Moon



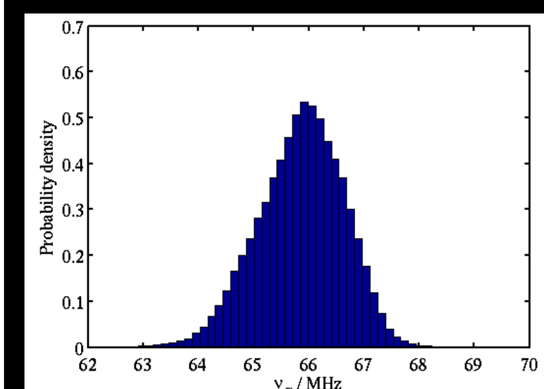


MCMC Approach to Signal Extraction

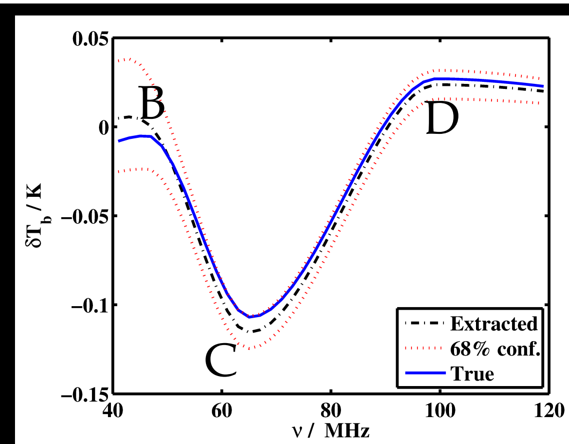




Turning Points B, C, D



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

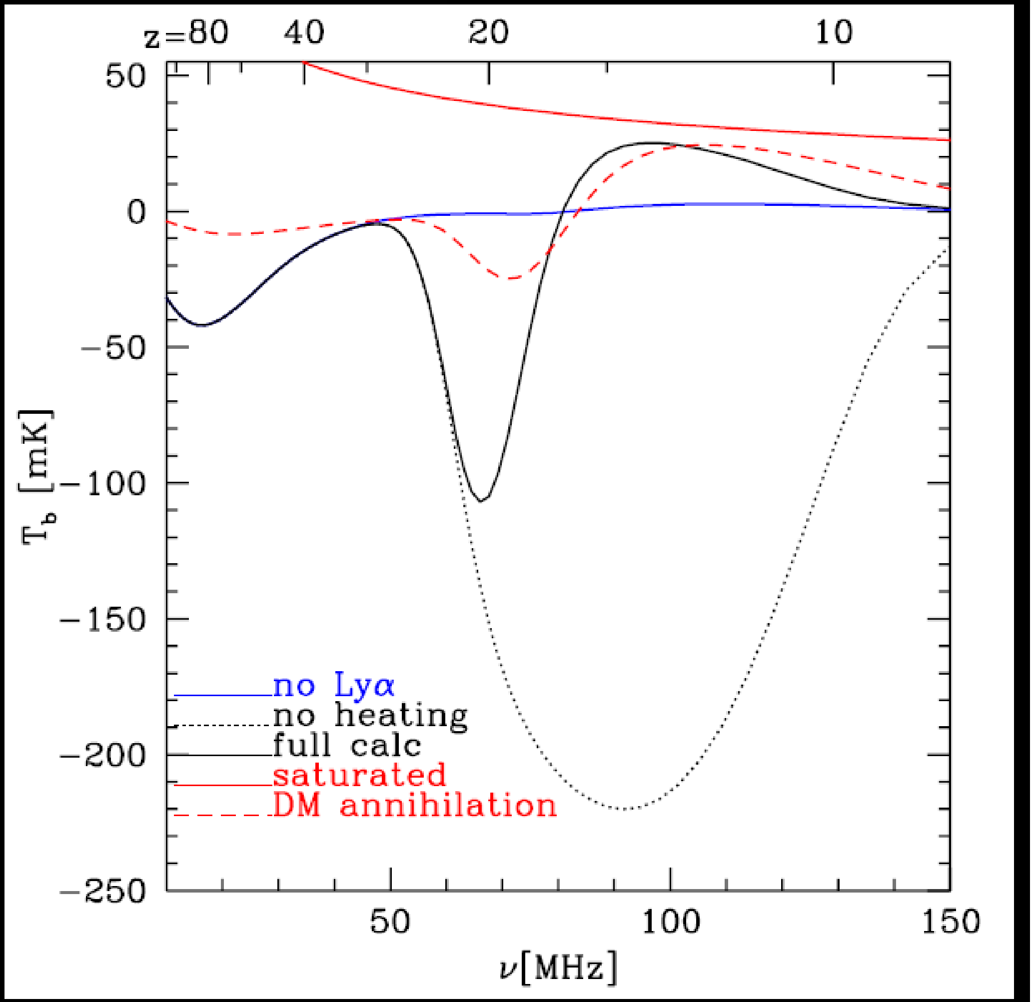


21 cm signal

(Harker et al. 2012, MNRAS, 419, 1070)

Alternative Signal Models

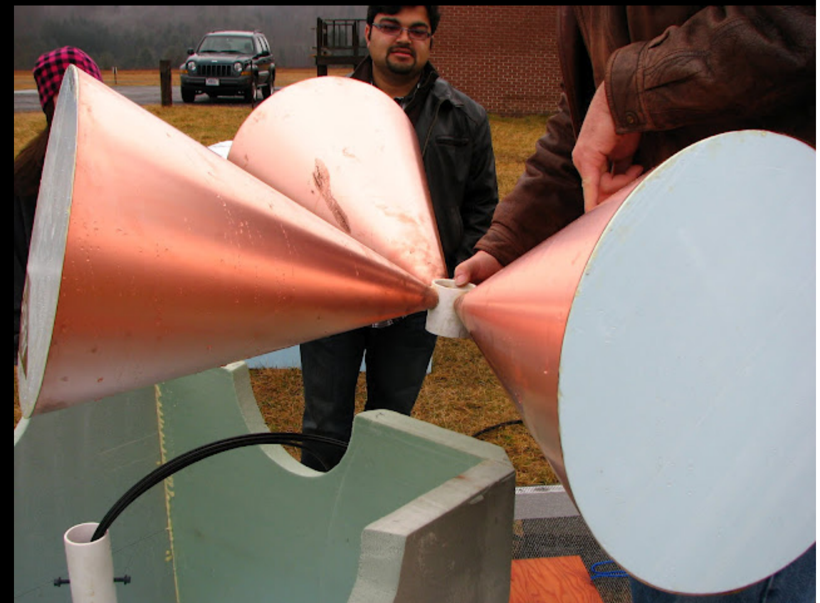
- Wide range of values for model parameters are allowed by current constraints
- Alternative models (e.g., including decaying dark matter) may not be described well by the turning points scheme.
- Exploring alternative parametrizations.

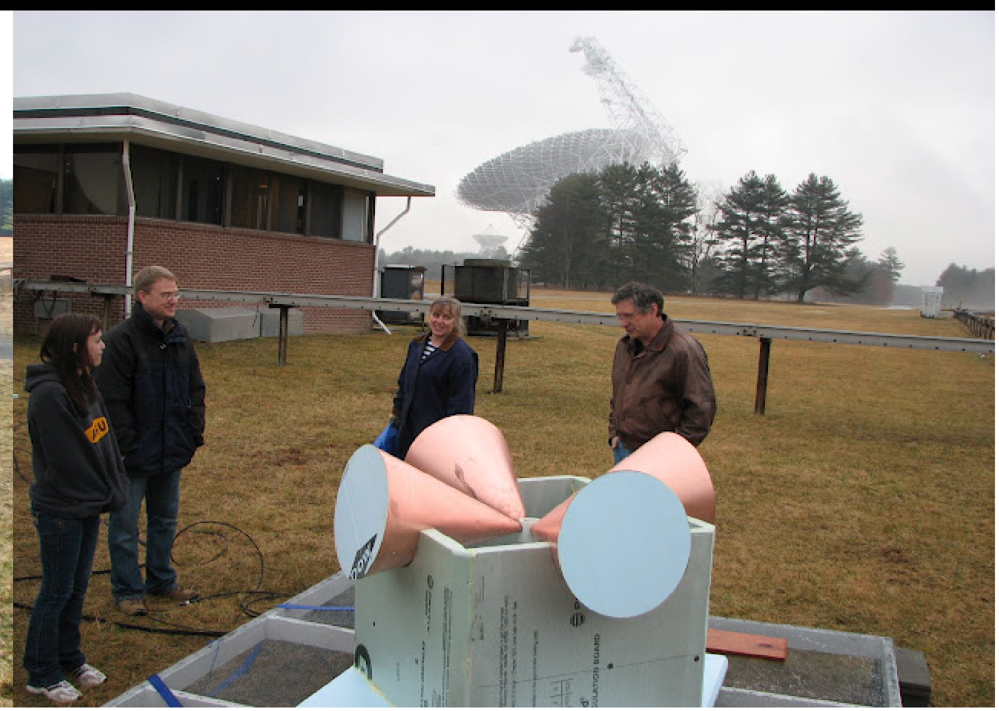


Pritchard & Loeb (2010)

Green Bank Field Tests

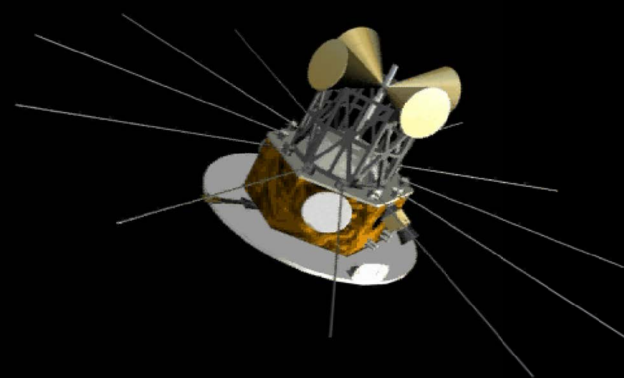
- Engineering prototype was deployed at the NRAO site in Green Bank, WV.
- Recorded data for about 2 weeks.
- Initial field tests validated the performance of three stages of DARE instrument: antenna, front-end, digital spectrometer.



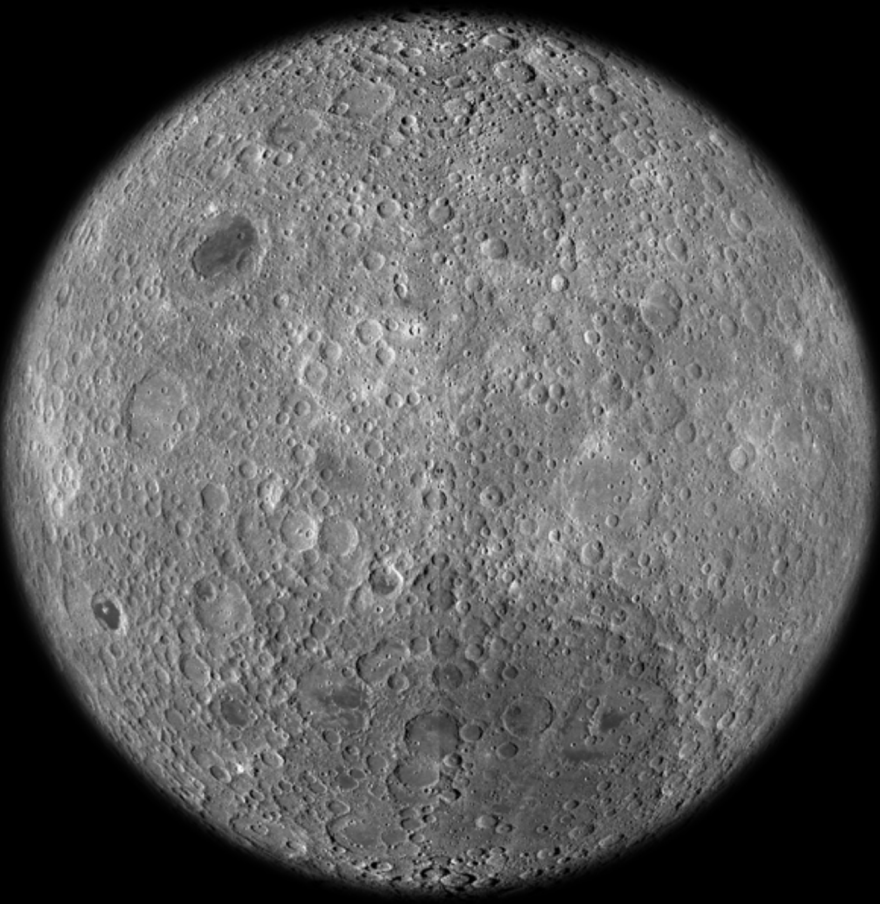


DARE Status & Timeline

- Proposed as a Explorer Mission in 2011 February
- Category II
- DARE Engineering prototype developed (NRAO and JPL)
- Instrument Verification Program includes the initial field tests in Green Bank, WV (Feb-Mar, 2012) as well as the DARE-ground experiment in Western Australia (Mar, 2012 onwards).
- Results from these experiments will be critical in re-proposing DARE for a SMEX mission in late 2013.



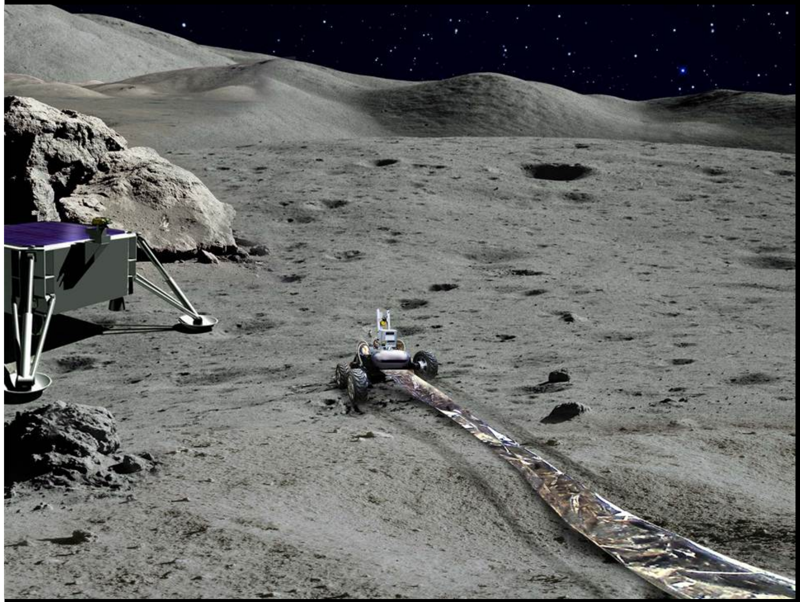
Lunar Farside



- Whole new, *unexplored* world in Earth's backyard!
- Farside always faces away from Earth and is only pristine radio-quiet site to pursue observations of Universe's *Cosmic Dawn*
- Farside includes the South Pole-Aitken basin – possibly the largest, deepest, & oldest impact basin in the inner solar system.
- Opportunity to demonstrate human-robotic exploration strategies needed to explore surfaces of the Moon, asteroids, & Mars.

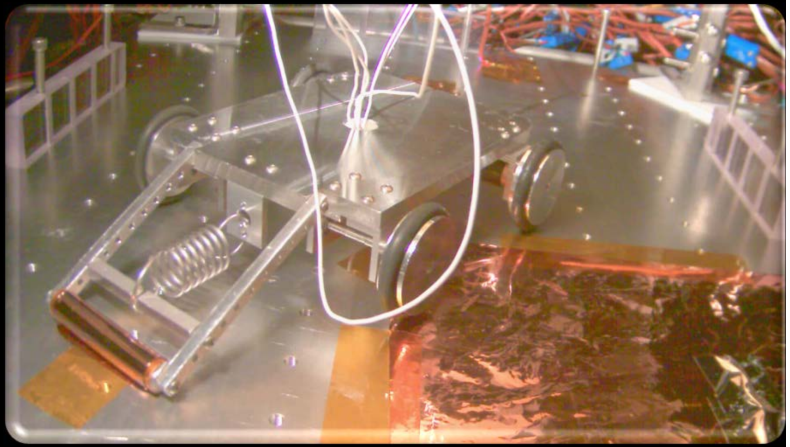
Deployment of Kapton Film Antennas

- Metallic conductor deposited on surface of Kapton film.
- Unrolled, deployed by rover
- Operate at ν < 100 MHz.
- Film tested in vacuum chamber, with thermal cycling & UV exposure similar to lunar surface conditions, & in the field.



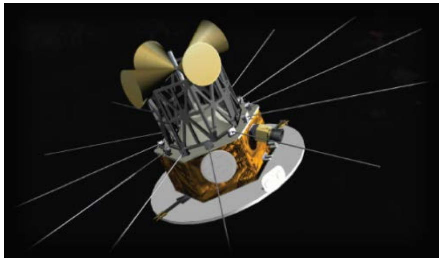
Artist's conception of roll-out Kapton film antenna on the Moon

Kapton antenna test in New Mexico



Rolling out Kapton film inside vacuum chamber with teleoperated mini-rover

Antenna Deployment



Dark Ages Radio Explorer (DARE)

DARE is designed to address:

- When did the First Stars ignite?
- When did the first accreting Black Holes turn on?
- When did Reionization begin?

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 zone in inner solar system.
- Using biconical dipole antennas with smooth response function & Markov Chain Monte Carlo method to recover spectral *turning points* in the presence of bright foregrounds.
- Using lessons from ground-based experiments and prototyping hardware

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