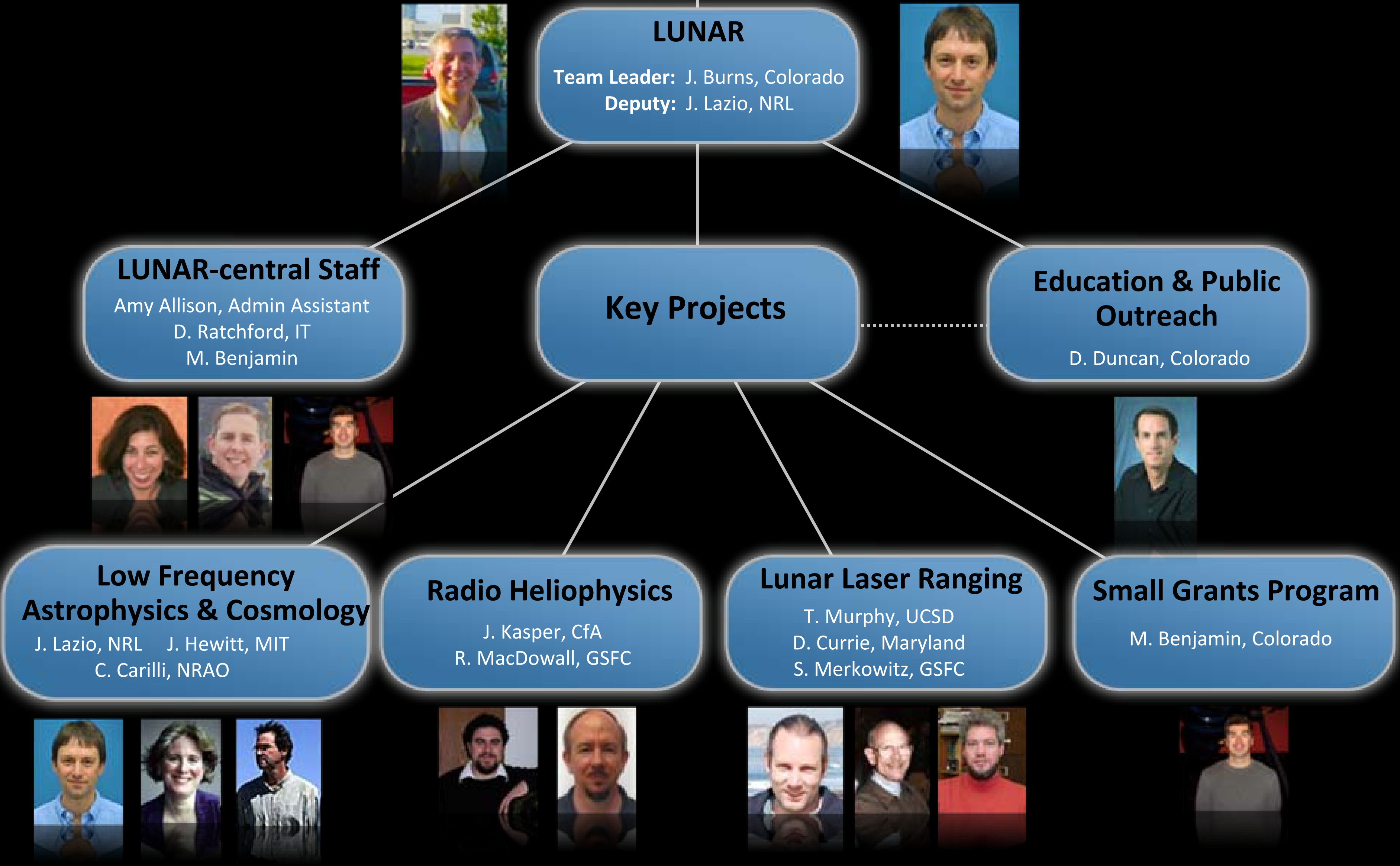
Exploring the Cosmos from the Moon

Jack Burns and the NLSI LUNAR Team
University of Colorado at Boulder and NLSI

University of Michigan, 1 April 2010

NASA LUNAR SCIENCE INSTITUTE



LUNAR

Team Leader: J. Burns, Colorado
Deputy: J. Lazio, NRL

LUNAR-central Staff

Amy Allison, Admin Assistant
D. Ratchford, IT
M. Benjamin

Key Projects

Education & Public Outreach

D. Duncan, Colorado

Low Frequency Astrophysics & Cosmology

J. Lazio, NRL   J. Hewitt, MIT
C. Carilli, NRAO

Radio Heliophysics

J. Kasper, CfA
R. MacDowall, GSFC

Lunar Laser Ranging

T. Murphy, UCSD
D. Currie, Maryland
S. Merkowitz, GSFC

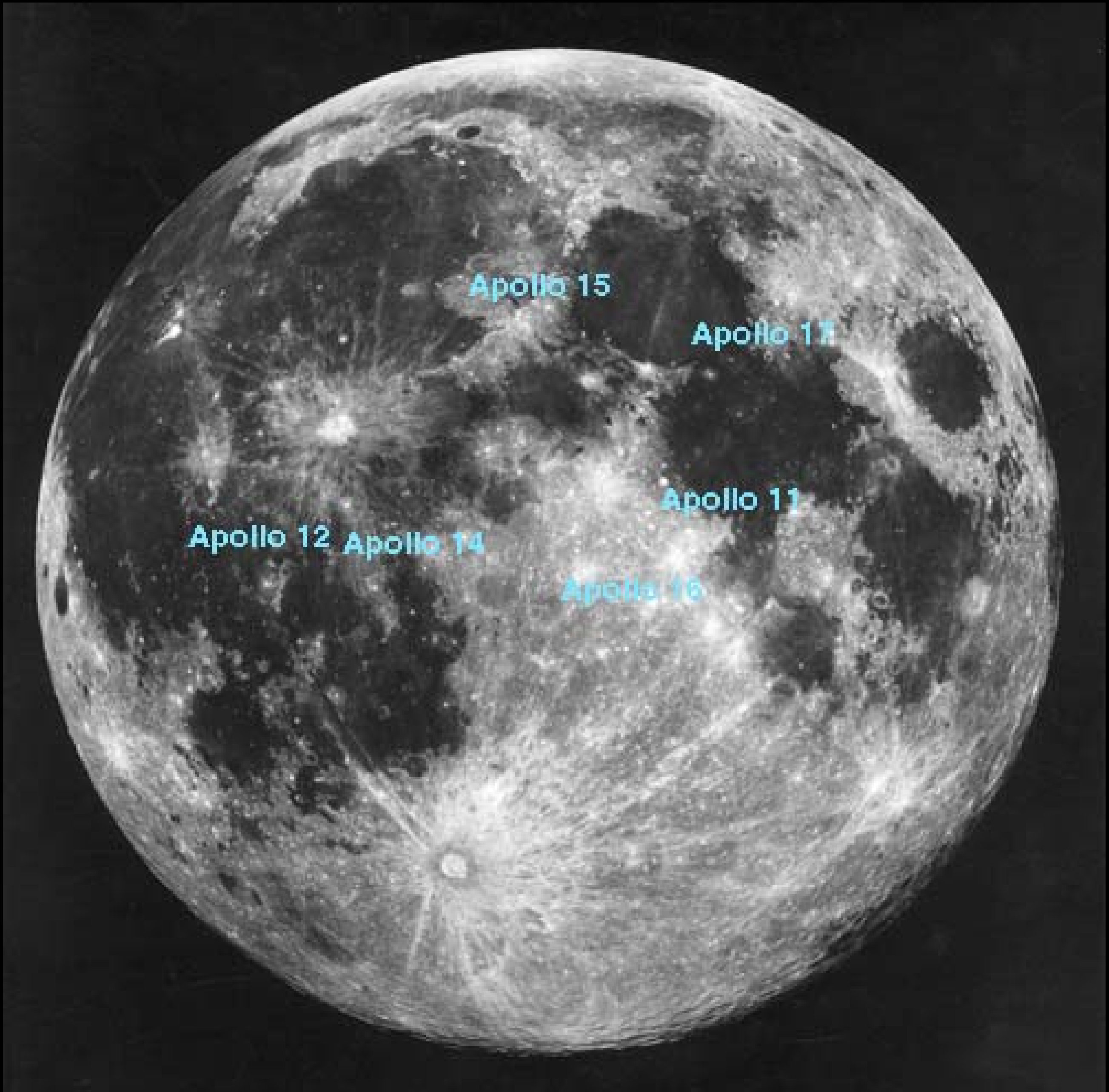
Small Grants Program

M. Benjamin, Colorado

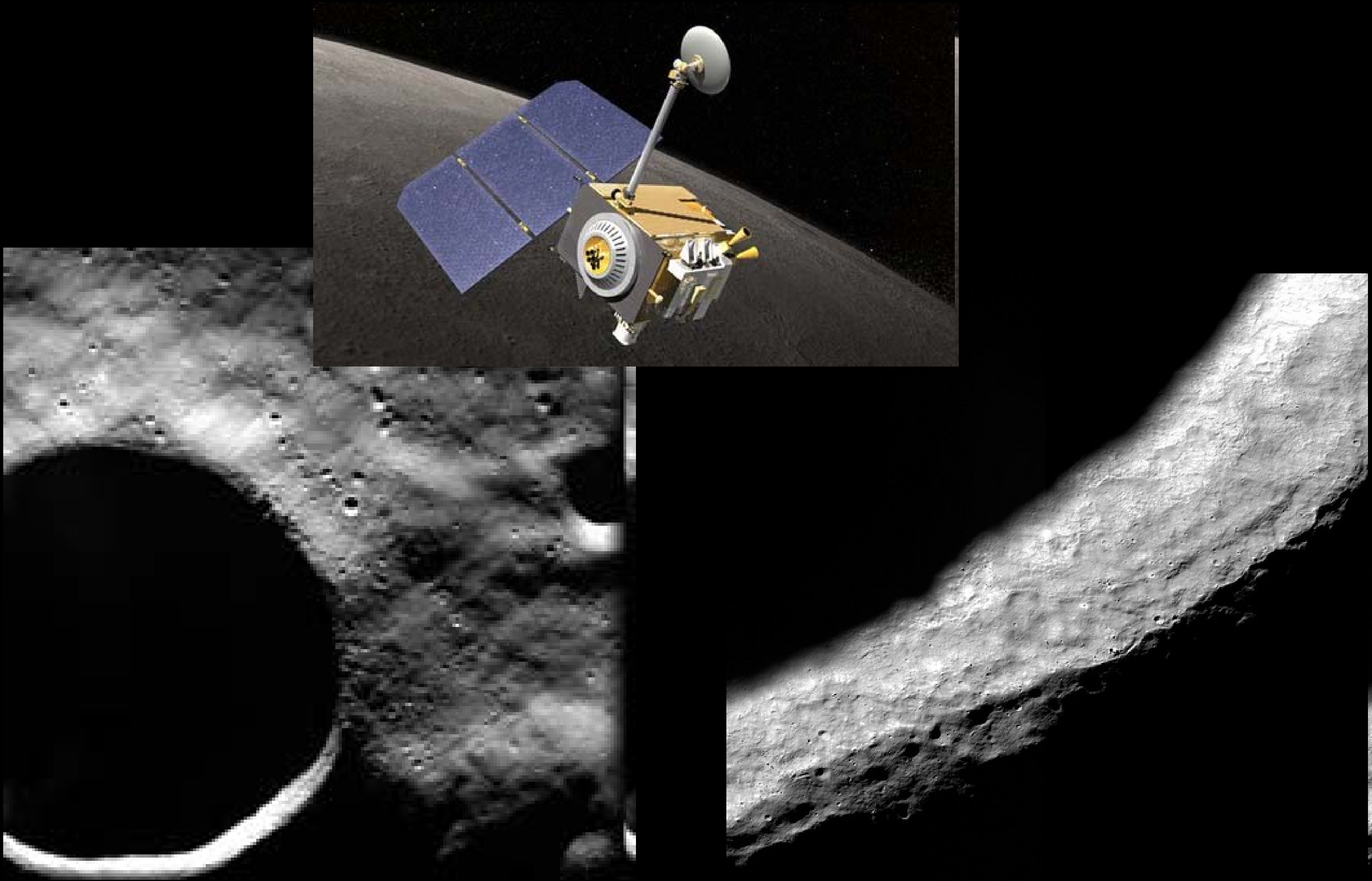
Destination Moon (1950)

Cat Women of the Moon (1953)

Apollo Landing Sites



Shackleton Crater at the Moon’s South Pole



NASA Lunar Science Institute

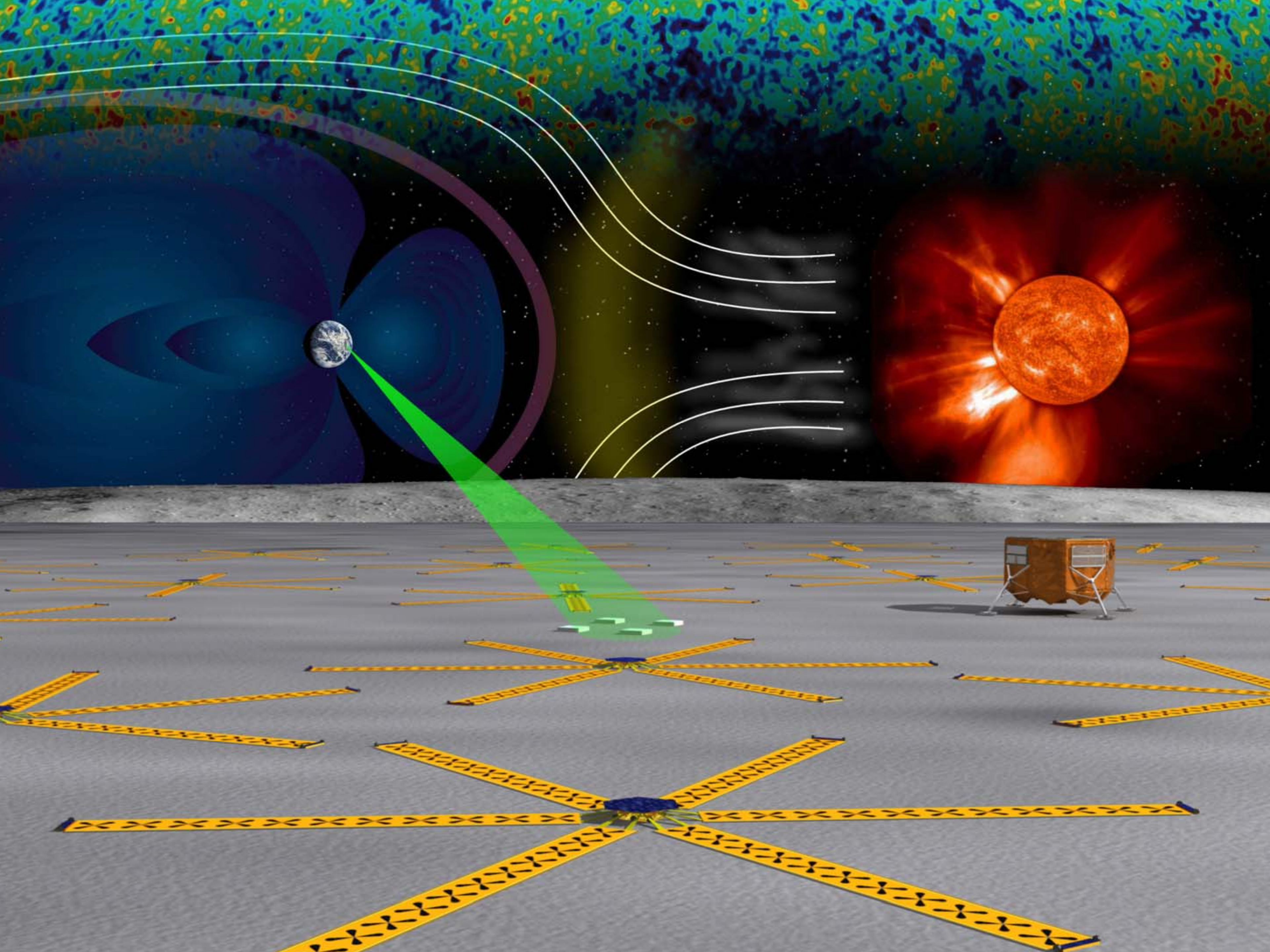
WHAT IS LUNAR SCIENCE?

For the NLSI, lunar science is broadly defined to include studies:

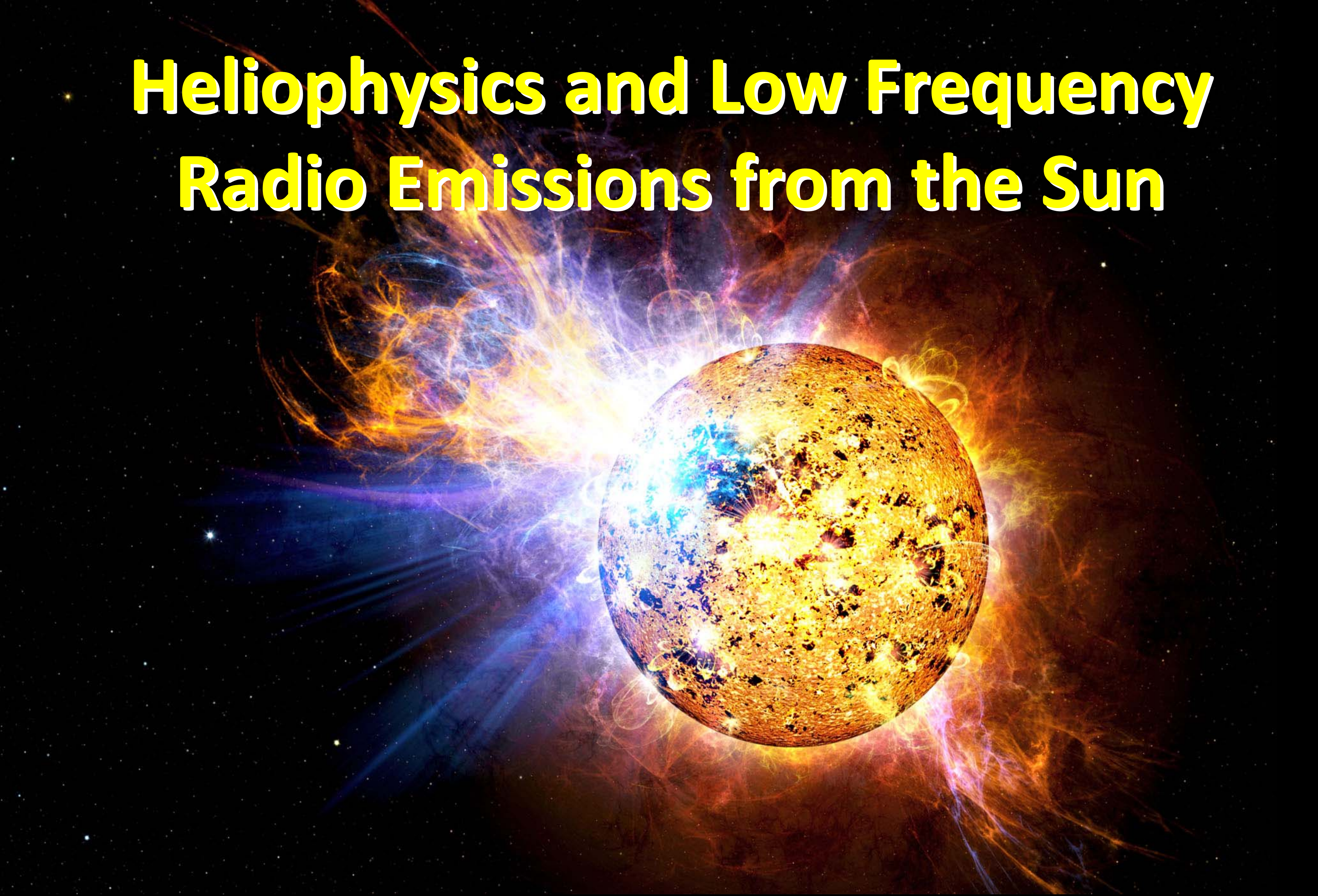
- ***Of the Moon:*** Investigations of the nature and history of the Moon (including research on lunar samples) to learn about this specific object and thereby provide insights into the evolution of our solar system

- ***On the Moon:*** Investigations of the effects of the lunar environment on terrestrial life and the equipment that supports lunar inhabitants, and the effects of robotic and human presence on the lunar environment

- ***From the Moon:*** Use of the Moon as a platform for performing scientific investigations, including observations of the Earth and other celestial phenomena that are uniquely enabled by being on the lunar surface.

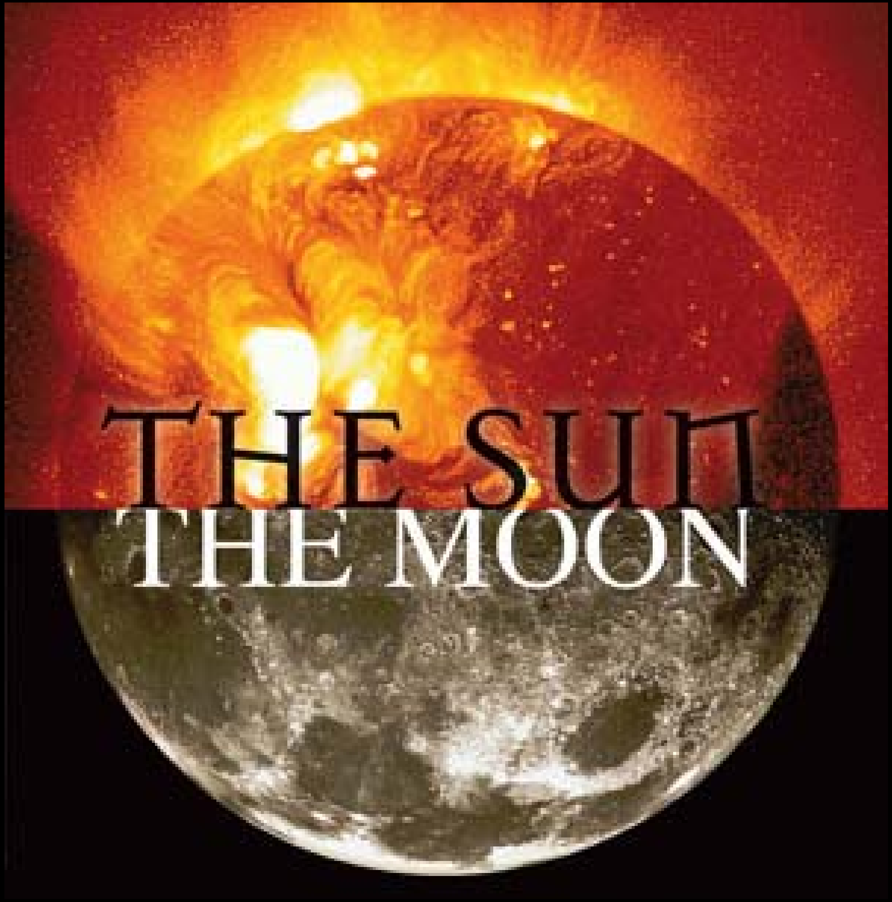


Heliophysics and Low Frequency Radio Emissions from the Sun



Radio Heliophysics from the Moon

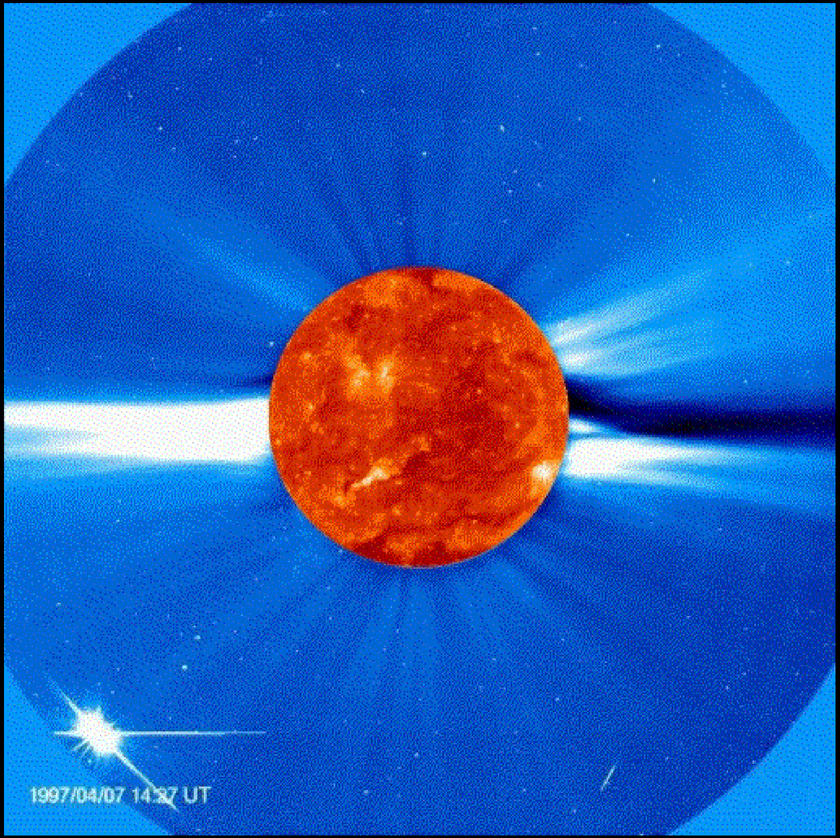
Lead Scientists: J. Kasper (CfA) and R. MacDowall (GSFC)



- How does cosmic ray acceleration occur within the heliosphere?
- A low frequency lunar radio array will produce the first resolved (≤2° at 10 MHz), high time resolution images of solar radio emissions from the outer corona.

Coronal Mass Ejections

- Gas blown from Corona
  - 10^{15} grams of gas (lower limit average)
  - 10^{12} W of power.
- Velocity range
  - 20 km/s to 3000 km/s
- Frequency Occurrence
  - 1/week @ Solar min
  - 2-3/day @ Solar max
- Location
  - Focused on equator during solar min
  - Varying latitudes during solar max
- Origin
  - Correlation to solar flares, prominences & sunspot regions
  - Also occur in absence of the above

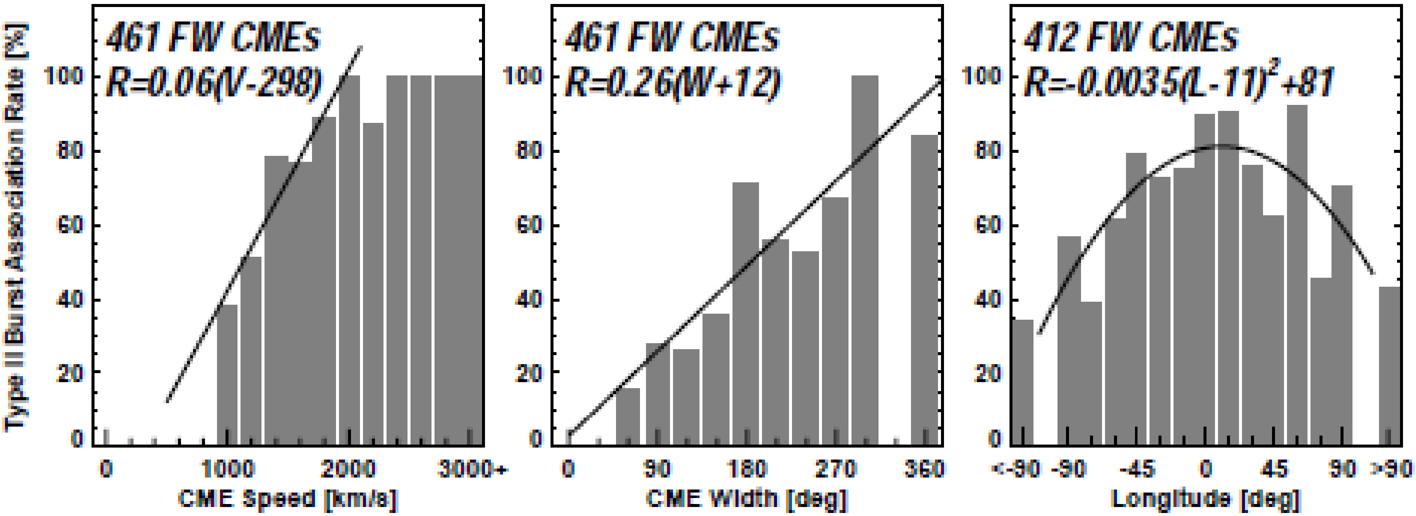


CME’s & Type II Radio Bursts

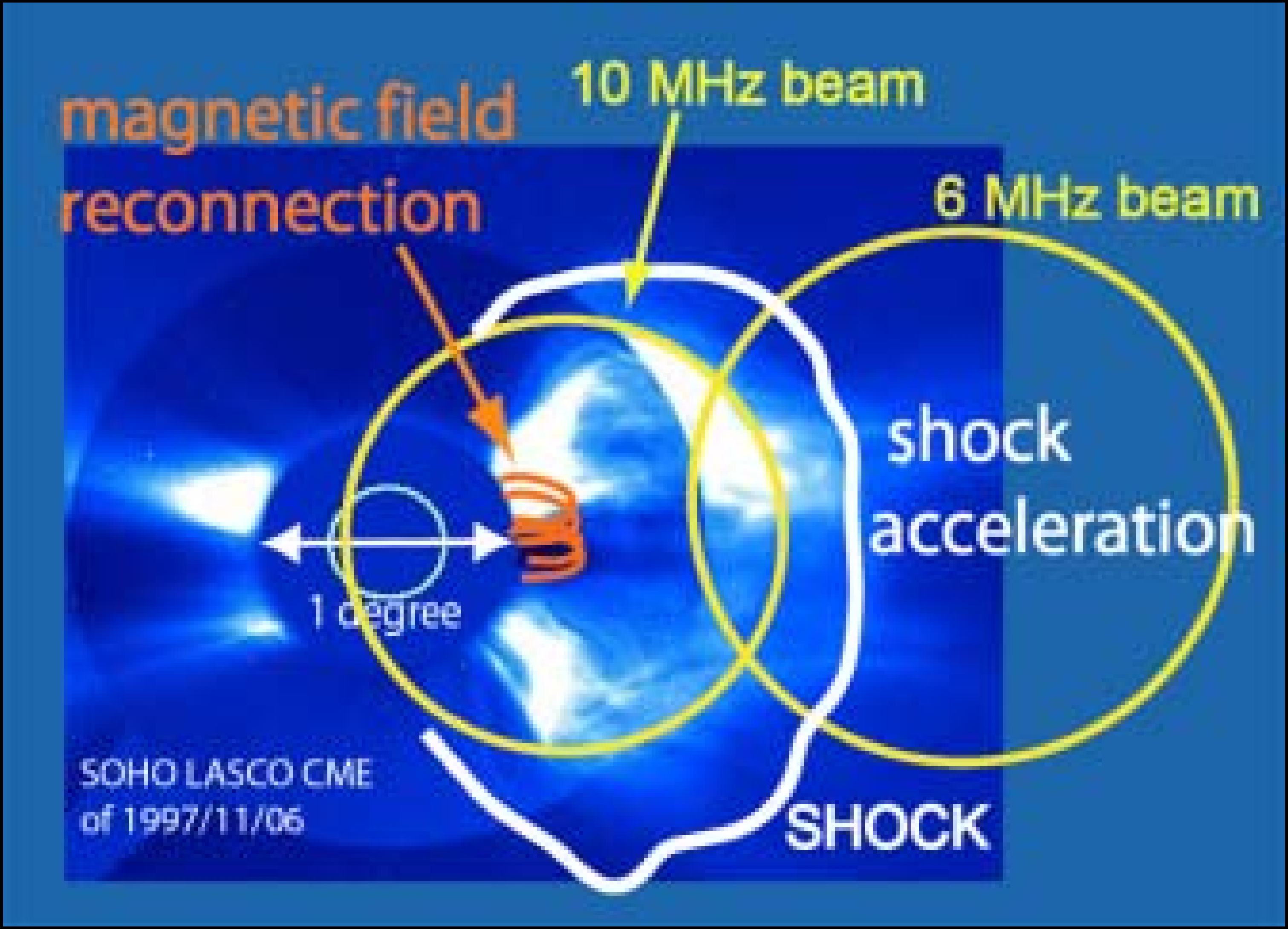
Gopalswamy et al. 2008, *Ann. Geophys.*, **26**, 3033.

Property	Radio-quiet	Radio-loud
Number of FW CMEs	193 (42%)	268 (58%)
Average speed	1117 km/s	1438 km/s
Average width	86°	89°
Fraction of halos	16%	60%
Median flare size	C6.9	M3.9
Fraction of backside CMEs	55%	25%
East-west asymmetry	−0.02	0.2
Center-to-limb variation	increase	decrease
SEP association[b]	none	55%

- Good correlation seems to exist between CMEs & Type II radio bursts. Statistically this relationship is proven.
- However not all Type II radio bursts are SEP (solar energic particle) event indicators.

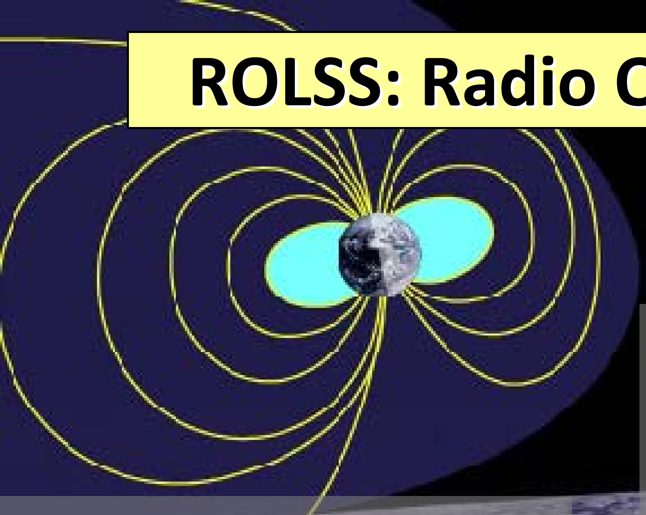


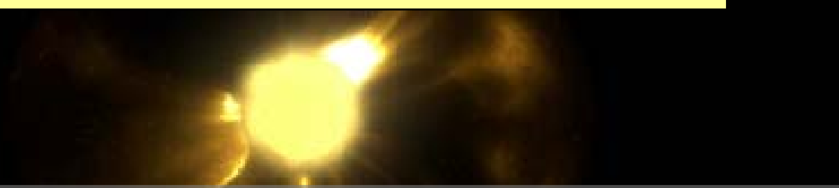
Imaging Solar Radio Bursts from a Lunar Array



SOHO LASCO CME of 1997/11/06

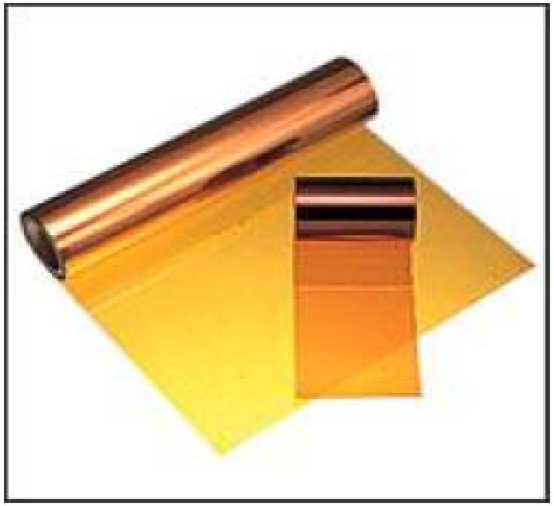
ROLSS: Radio Observatory for Lunar Sortie Science

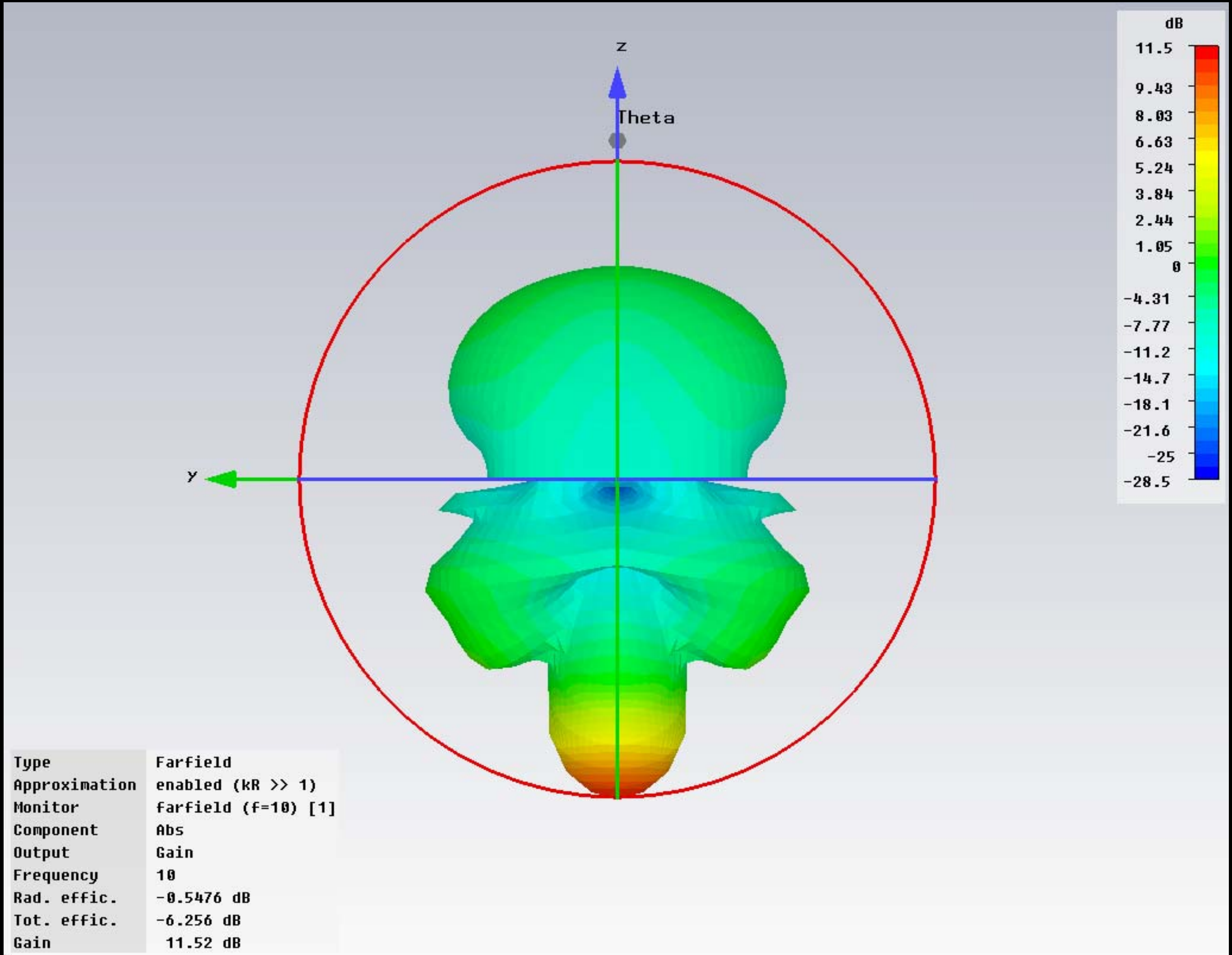




- **A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km). Operating at 1-10 MHz (30-300 m). Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.**
- **Conduct basic lunar science by tracking over time the density of the ionized lunar atmosphere (ionosphere).**

- Arms are thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).

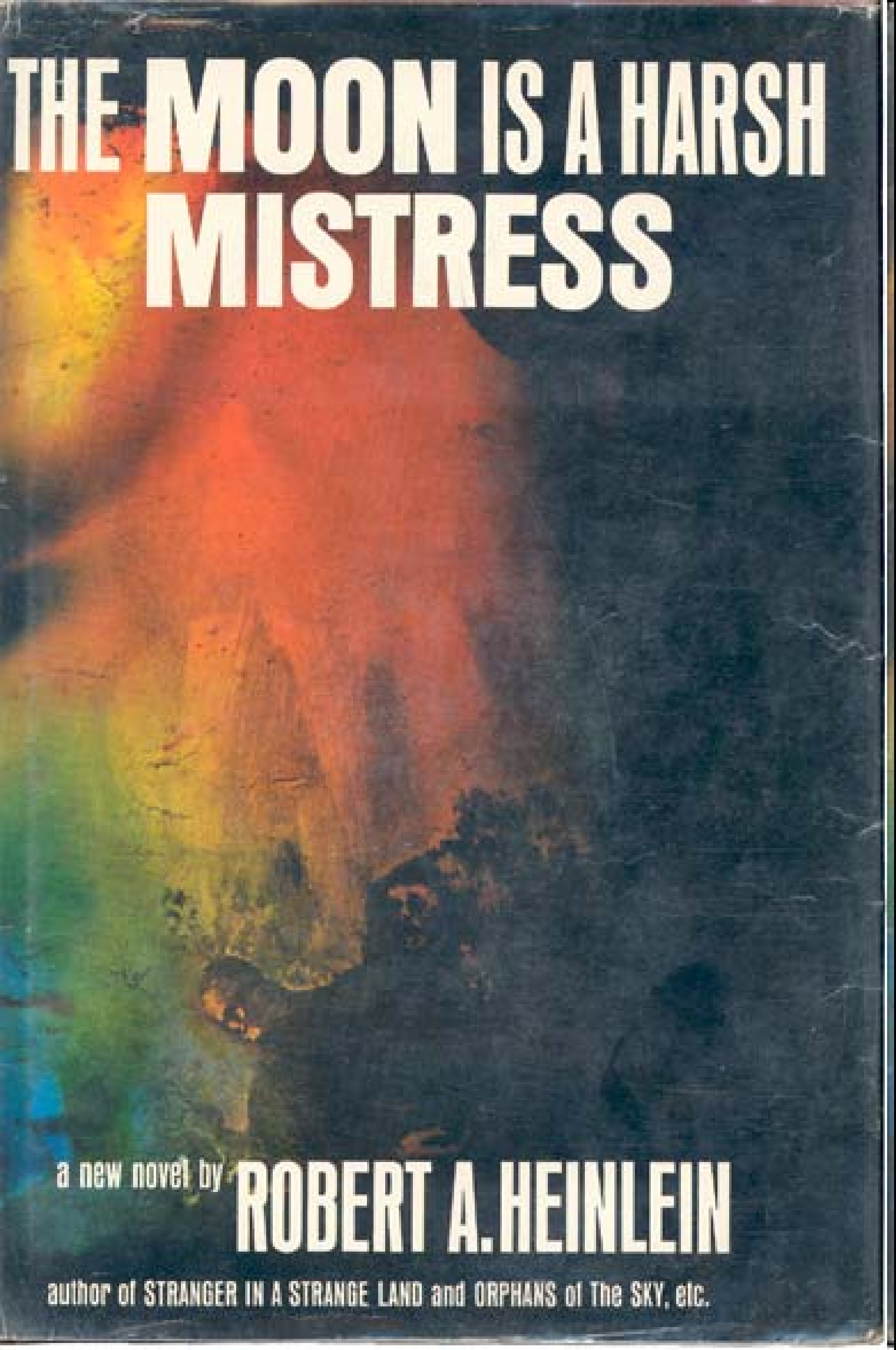




Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=10) [1]
Component	Abs
Output	Gain
Frequency	10
Rad. effic.	-0.5476 dB
Tot. effic.	-6.256 dB
Gain	11.52 dB

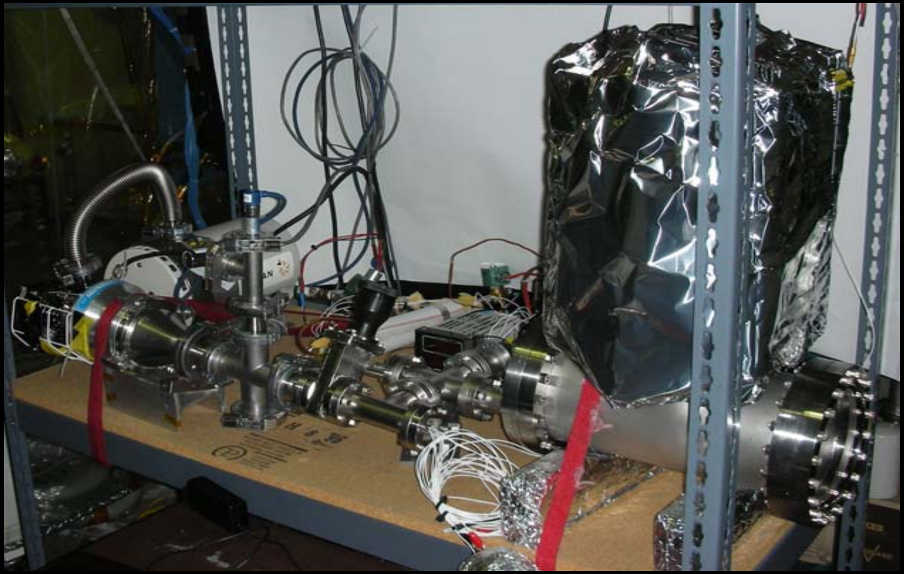
K. Stewart (NRL), D. Jones (JPL), K. Weiler (NRL) & LUNAR

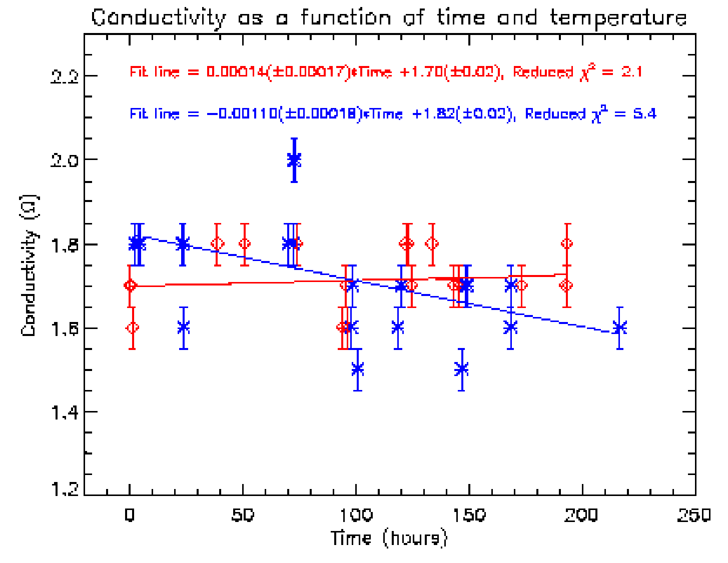
Gain and impedance calculations for thin film antennas on the Moon using realistic values for the electromagnetic properties of the lunar regolith. This determines requirements for transmission line designs and is necessary to understand how much power is delivered into the receiver, which in turn affects the entire electronics package.



- Day to Night temperature varies from 100 C to -150 C.
- Extreme ultraviolet light exposure during lunar day.
- Solar cosmic ray irradiation.
- Micrometeorite bombardment.

Laboratory Testing of Polyimide Film as Low Frequency Antenna Backbone



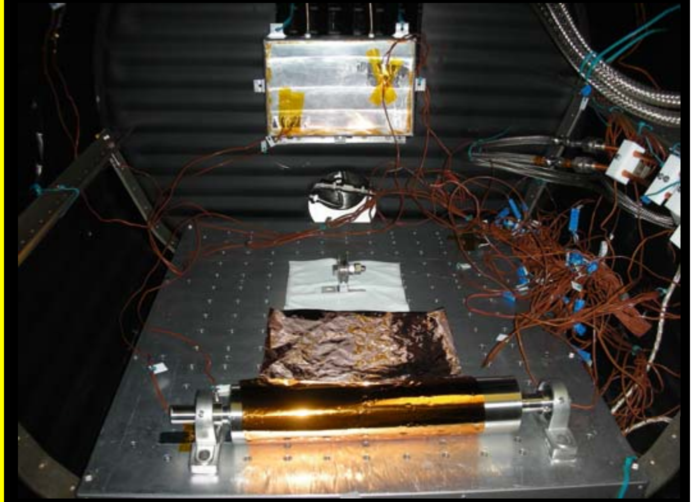


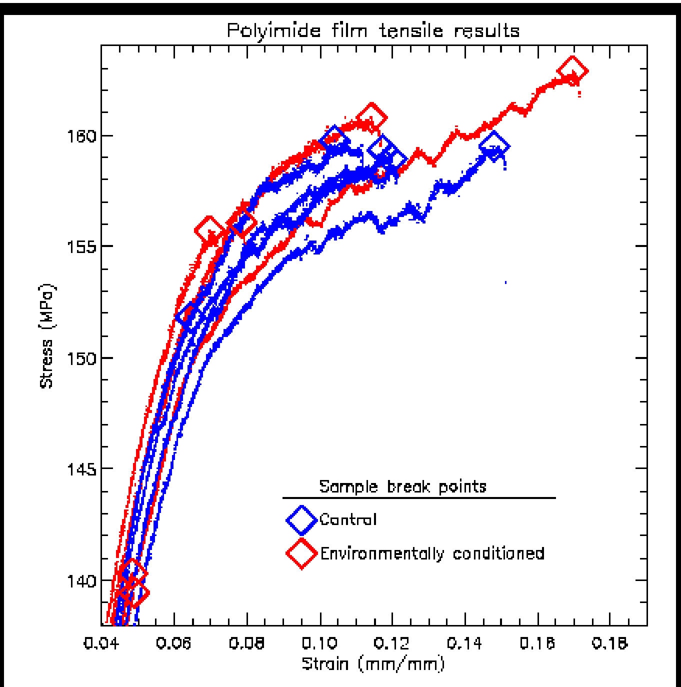
Experimental Set-up

- 12 24-hr duty cycles with T = -150 C to 100 C.
- Exposed to UV with deuterium lamp during "day cycle".

Results

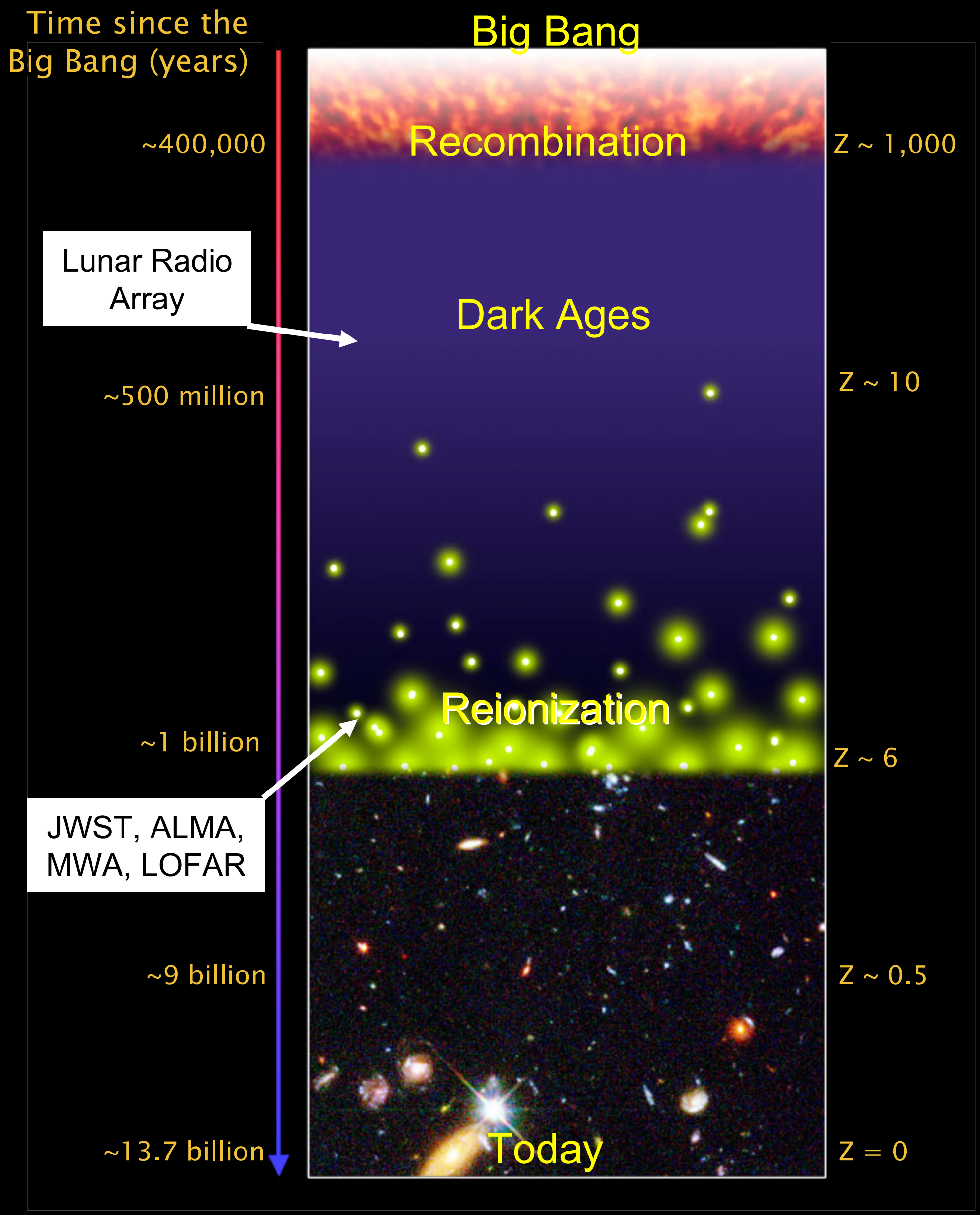
- No significant change in material or electrical characteristics during thermal cycling.



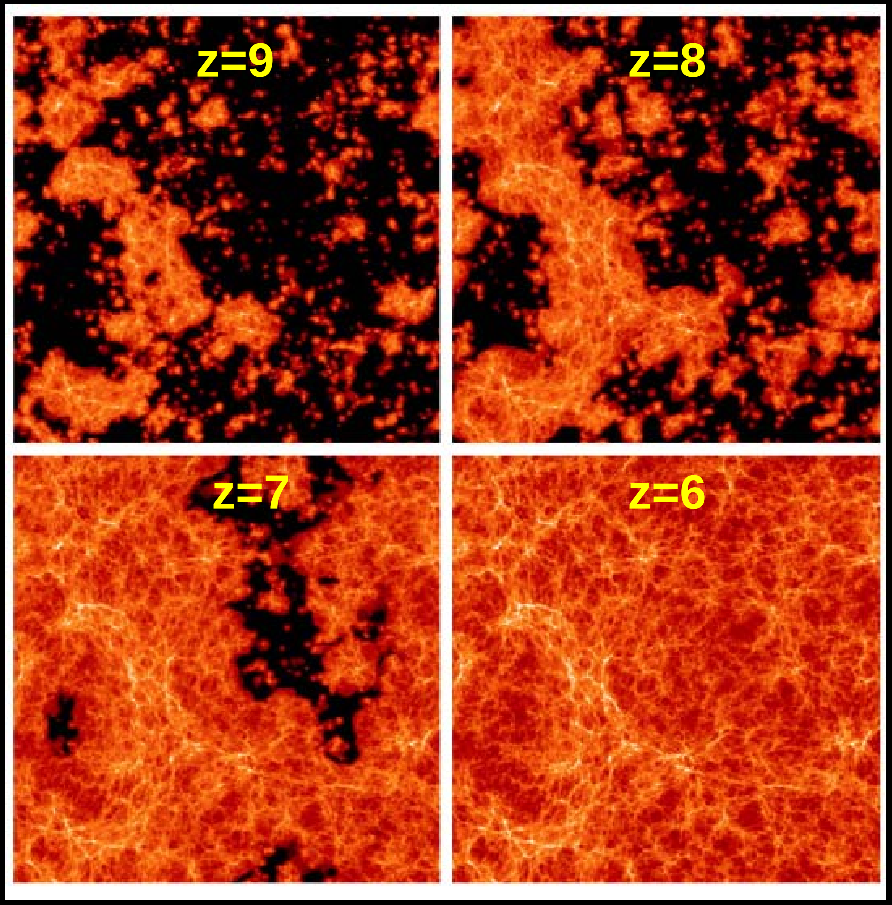


Reionization and the Dark Ages

Lead Scientists: J. Lazio (NRL), J. Hewitt (MIT), C. Carilli (NRAO)

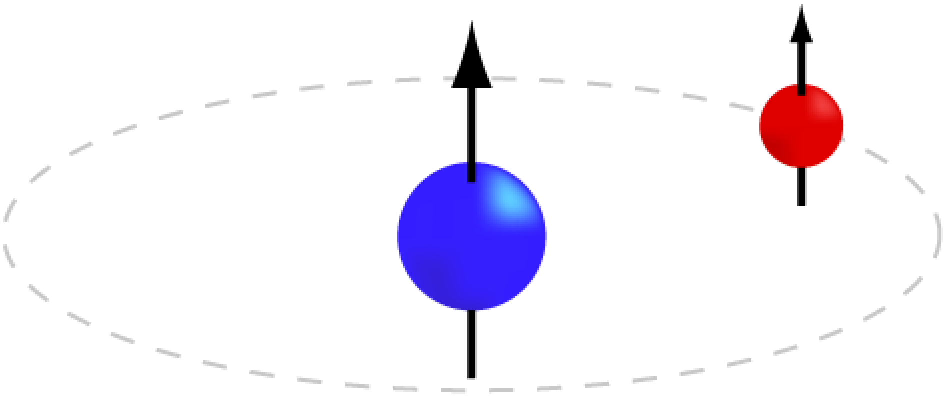


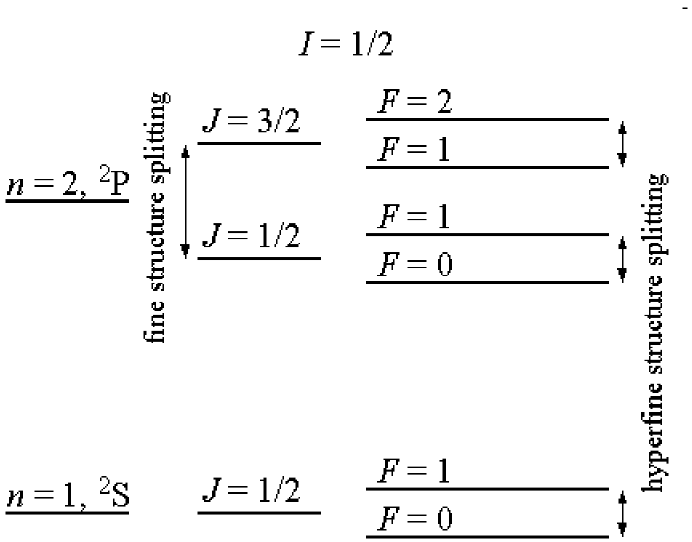
Reionization



Trac & Cen (2007). HII density is orange. HI is black. 50 h^{-1} Mpc on a side.

The 21-cm spectral line from HI



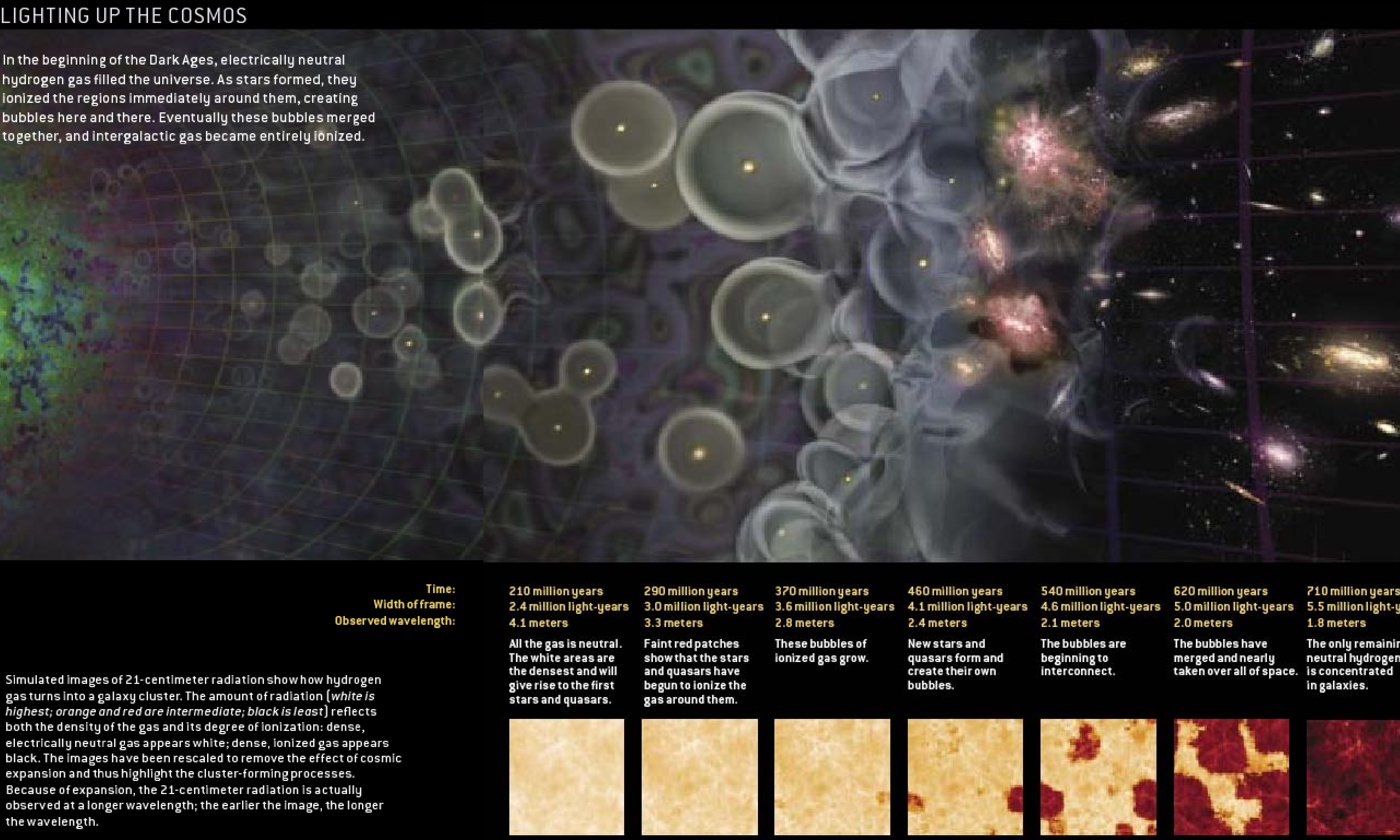


21 (1+z) cm = 1420/(1+z) MHz
at z=10, λ = 2.3 m (130 MHz)
at z=50, λ = 10.7 m (30 MHz)

$$\frac{\delta T_{\rm b}}{\rm mK} = 39h(1+\delta)x_{\rm HI}\left(1-\frac{T_{\rm CMB}}{T_{\rm spin}}\right)\left(\frac{\Omega_{\rm b}}{0.042}\right)\left[\left(\frac{0.24}{\Omega_{\rm m}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\mathrm{e}^{-T_*/T_{\rm spin}}$$

The Dark Ages Viewed via the Highly Redshifted 21-cm Line



LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

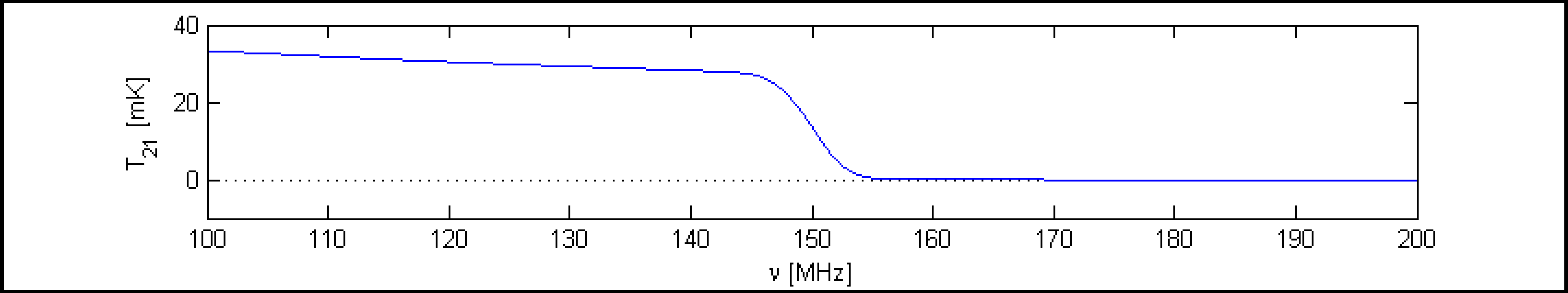
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-y
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters
	All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.	Faint red patches show that the stars and quasars have begun to ionize the gas around them.	These bubbles of ionized gas grow.	New stars and quasars form and create their own bubbles.	The bubbles are beginning to interconnect.	The bubbles have merged and nearly taken over all of space.	The only remainin neutral hydrogen is concentrated in galaxies.

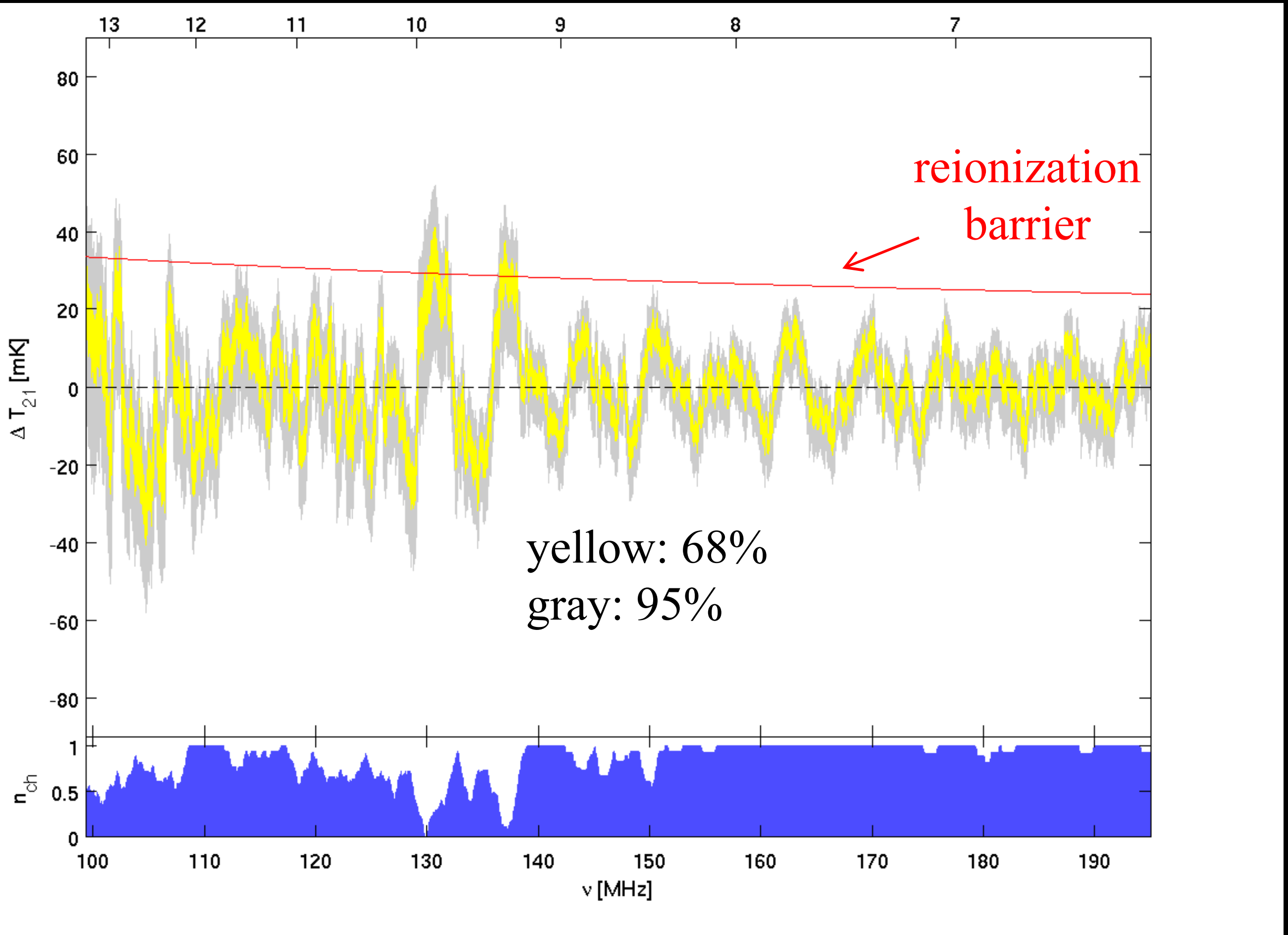
Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.

Loeb, A. 2006, *Scientific American*, 295, 46.

EDGES – Limits on Prompt Reionization

J. Bowman, Caltech & LUNAR



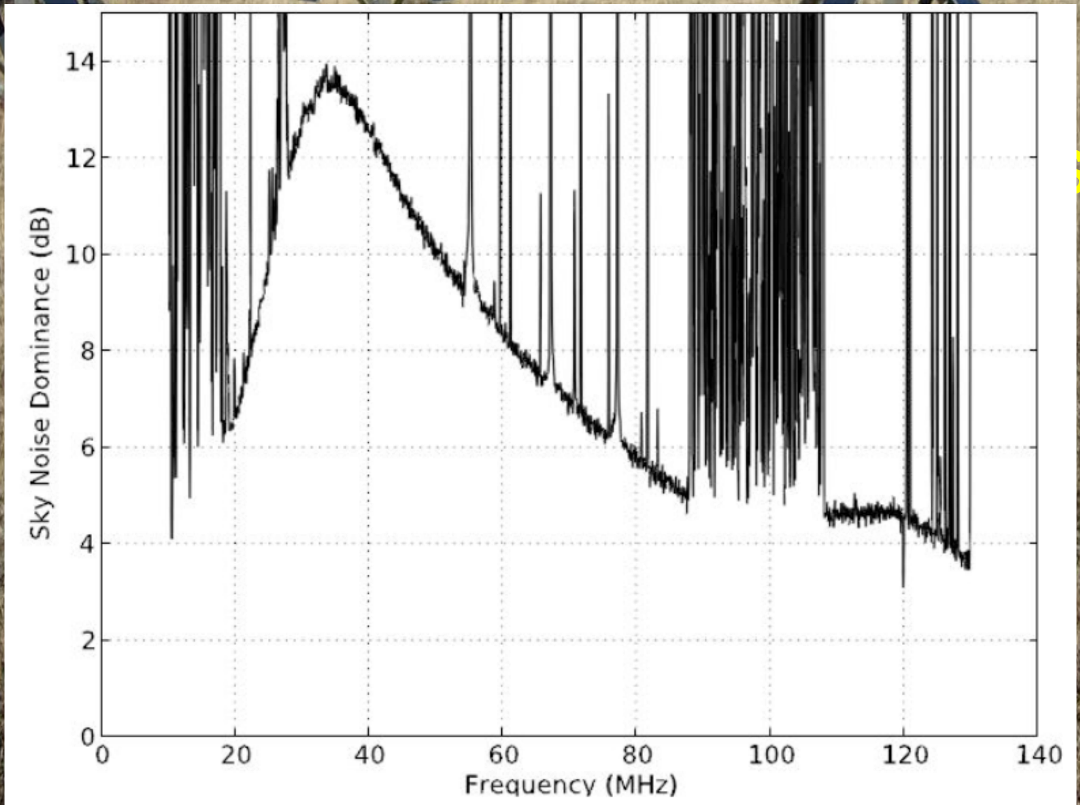


reionization barrier

yellow: 68%
gray: 95%

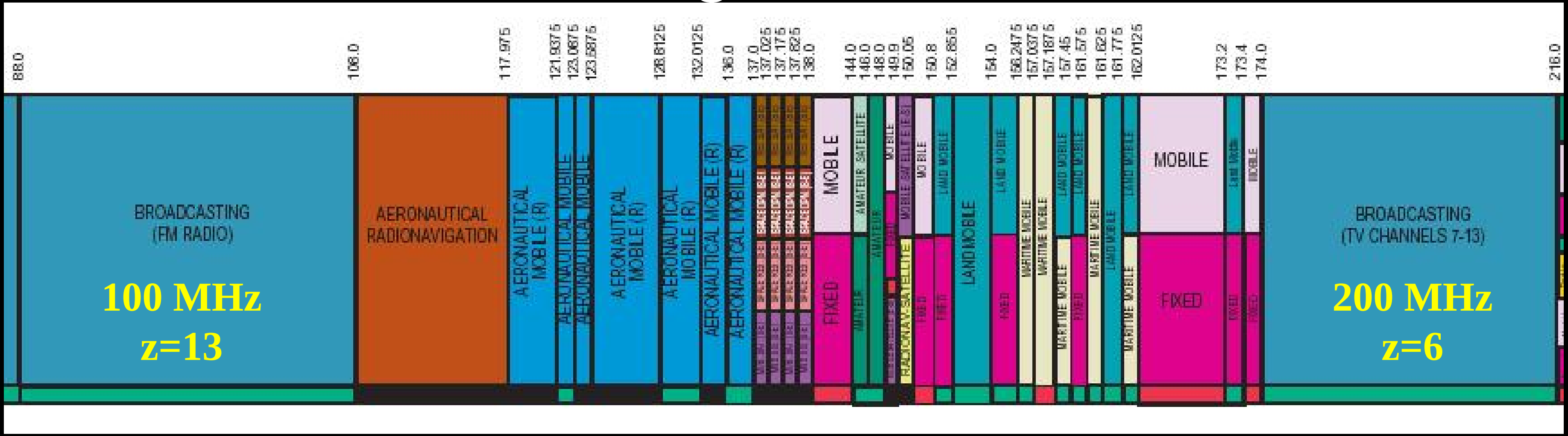
Primary Challenge for Earth Arrays: Interference/Ionosphere

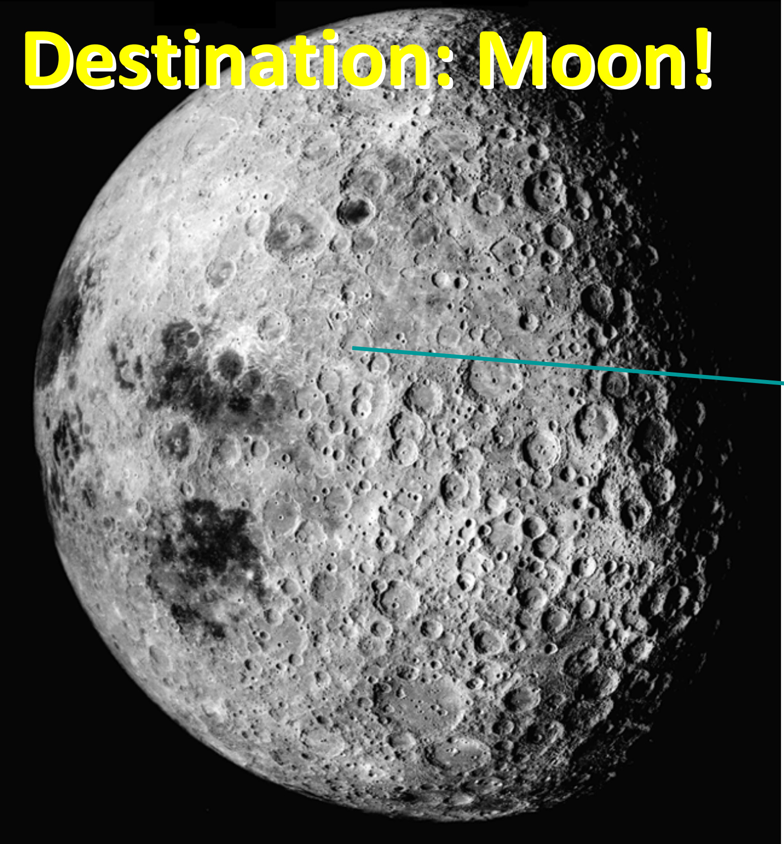
Long Wavelength Array
(VLA site in NM)



sting &

Lunar Advantage: No Interference!





Destination: Moon!

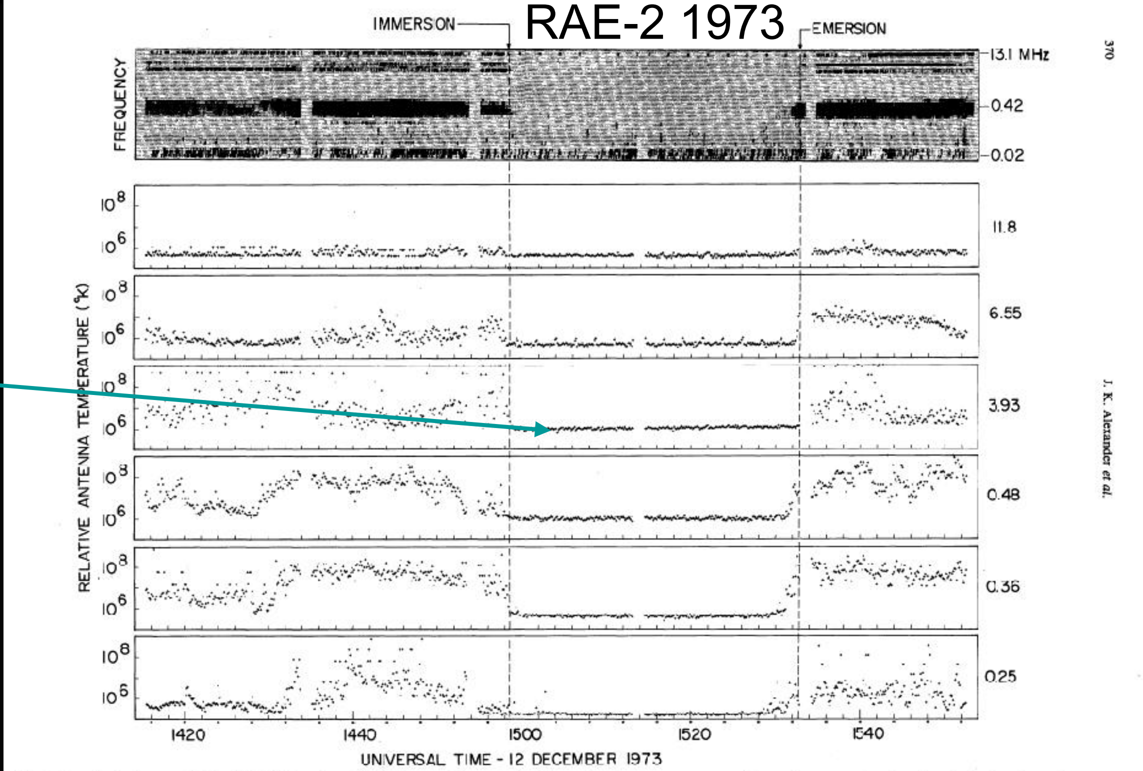
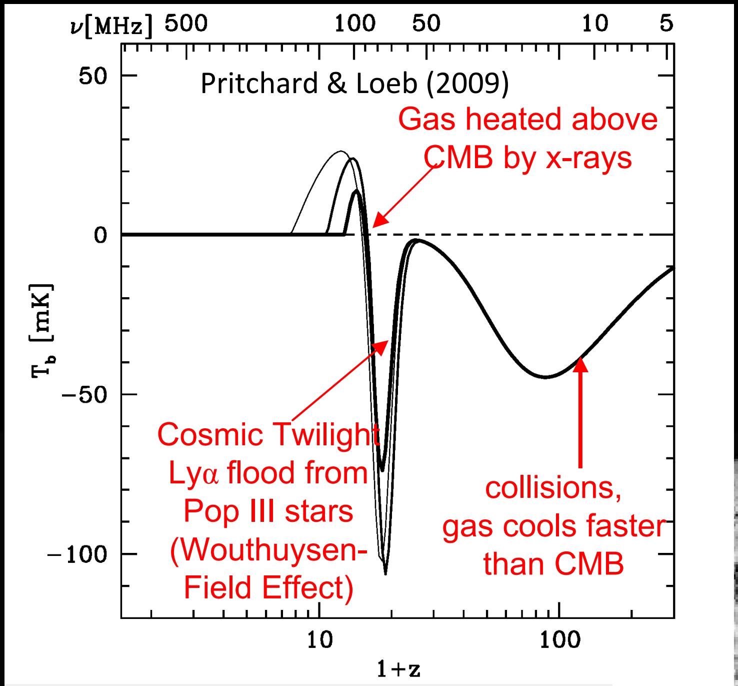
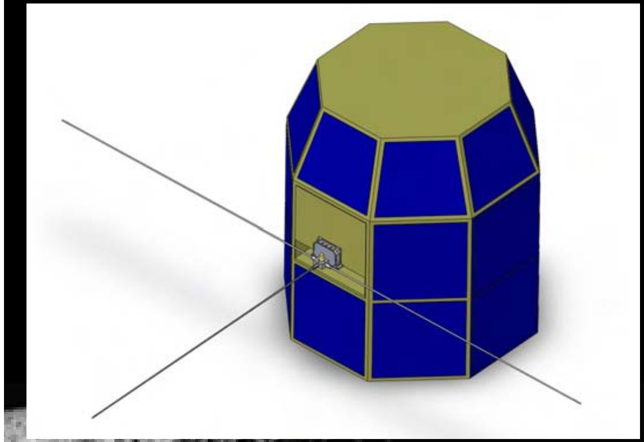


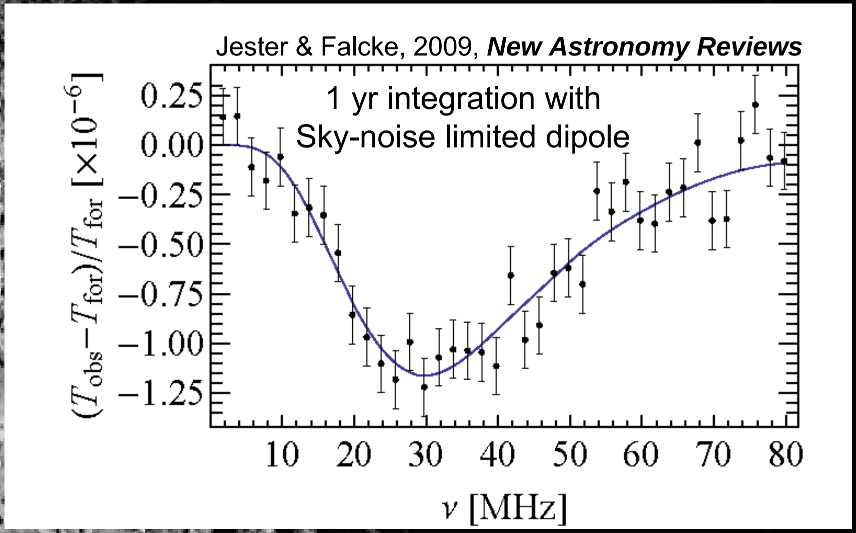
Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver and the burst receiver are tuned to the same frequency

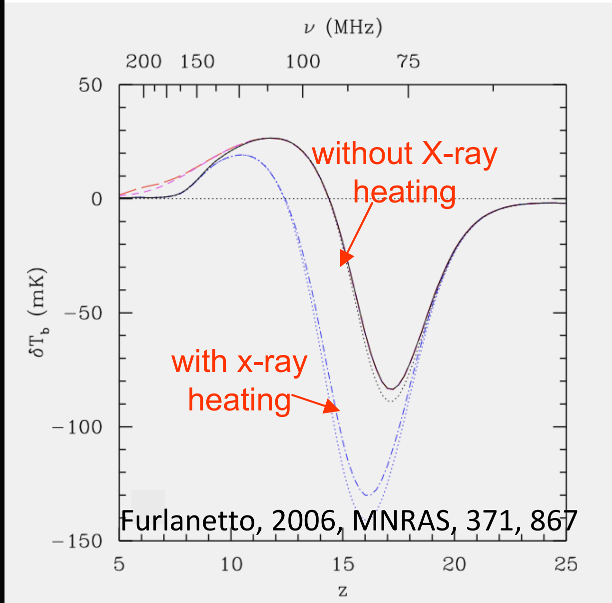
The Global (sky-averaged) HI Signal


Pritchard & Loeb (2009)



Global signal can be detected by single dipole in orbit above lunar farside!


Jester & Falcke, 2009, ***New Astronomy Reviews***

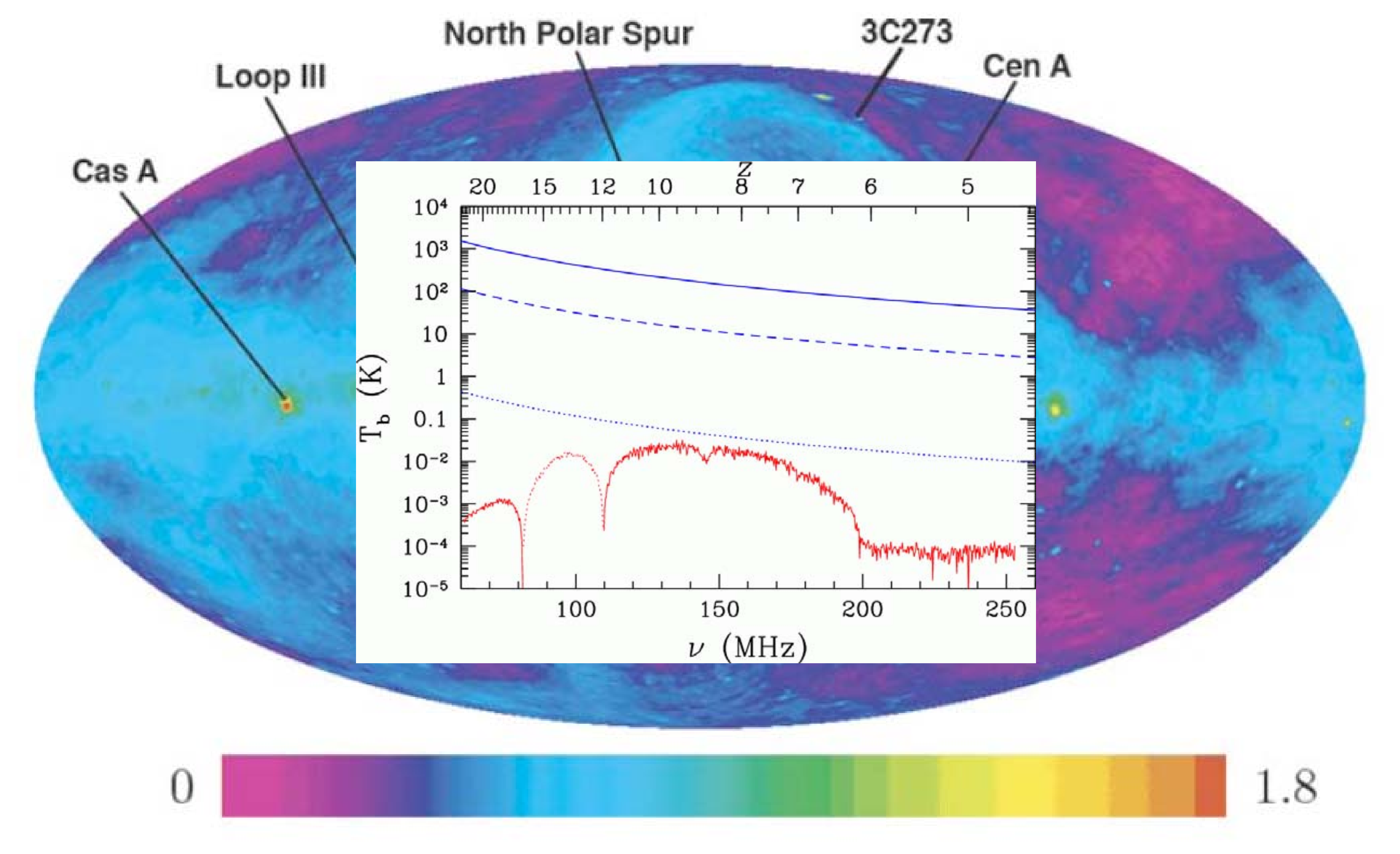

Furlanetto, 2006, MNRAS, 371, 867

$$\Delta T_{min} = T_{sys}/(\Delta\nu \cdot t)^{1/2}$$

where T_{sys} = sky temperature ~17,000 K at 30 MHz

Remaining challenge: Low Frequency Foreground

Nonthermal Galaxy Emission: $T_B = 100\ (\nu/200\ \mathrm{MHz})^{-2.7}\ \mathrm{K}$



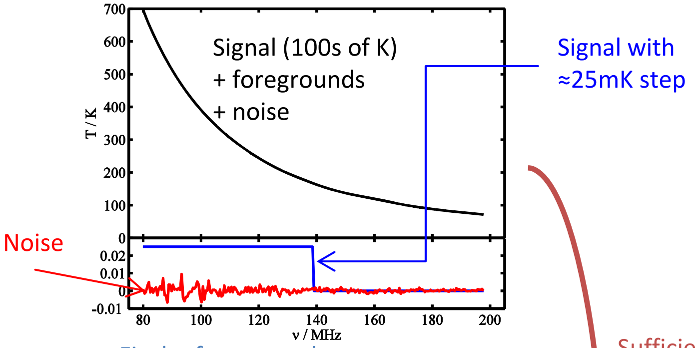
de Oliveira-Costa et al. (2008)

=>Solution: fitting in the spectral domain

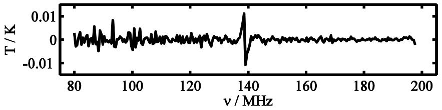
Foreground fitting for single-dipole and interferometric EoR experiments

G. Harker, U. Colorado & LUNAR

A dipole experiment like EDGES gives us a 'whole sky' integrated frequency dependence: experience here is likely to be valuable for a lunar-orbiting dipole experiment.



Fit the foregrounds non-parametrically and subtract them

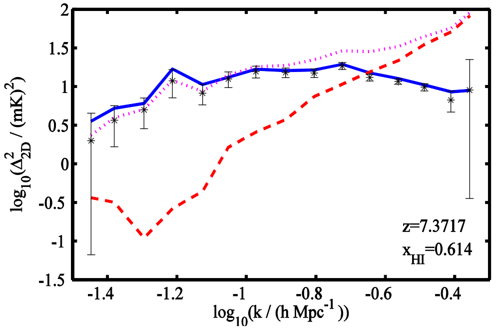


Detect a transition using e.g. a wavelet analysis

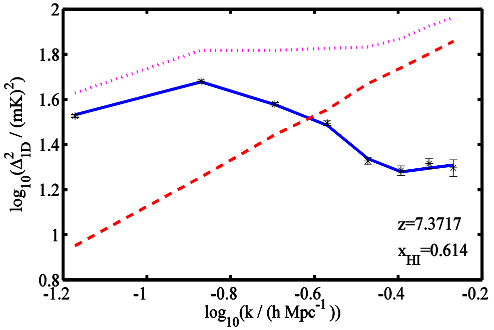
Constraints on the history of ionization and heating

Sufficiently strong assumptions allow us to fit models for the foregrounds and brightness temperature history to the data

Interferometry gives us spatial information, allowing a power spectrum analysis and (eventually) imaging, to help constrain cosmology, the first objects and maybe exotic physics



Angular power spectrum



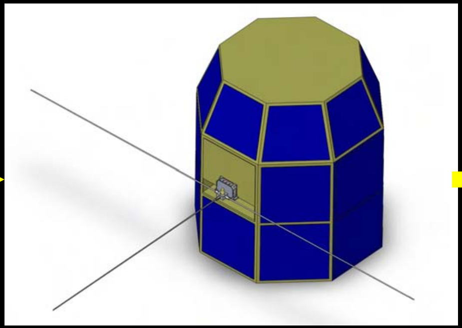
Line-of-sight power spectrum

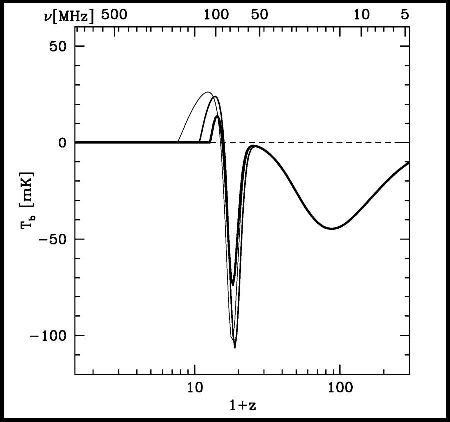
A simulation of 900 hrs of observation with LOFAR (Harker et al. 2010), using non-parametric foreground fitting to extract the power spectrum (points - extracted signal; blue – input signal; red – noise; magenta – residuals)

Roadmap to the Early Universe via Earth & the Moon

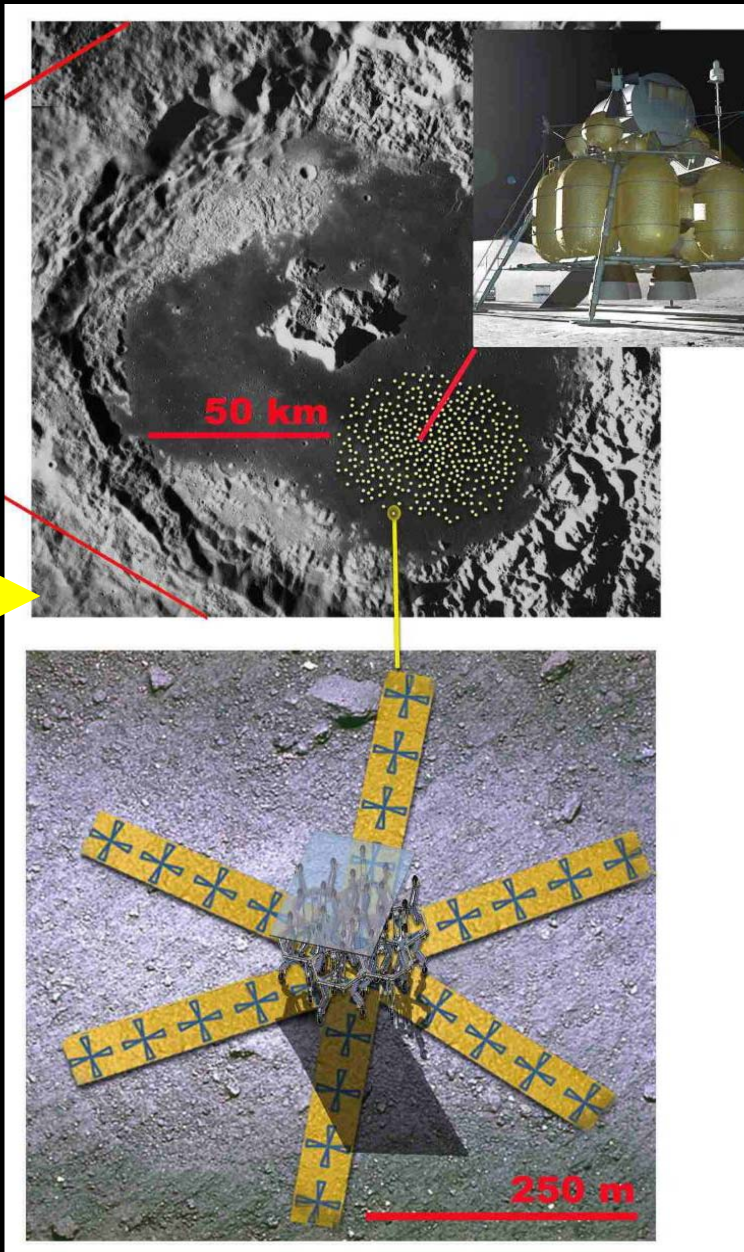
Ground-based telescopes

Lunar Orbit

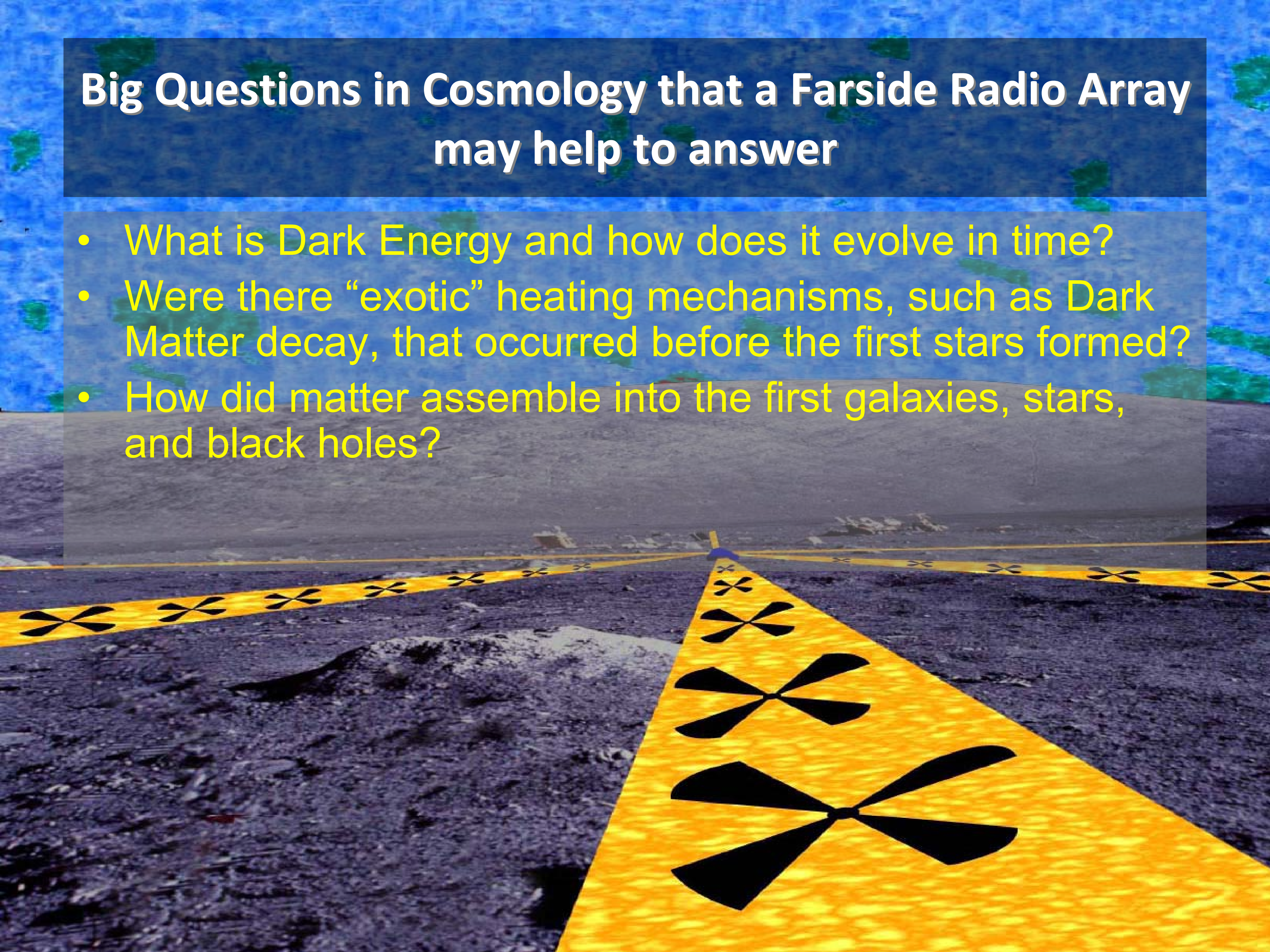




Lunar Farside

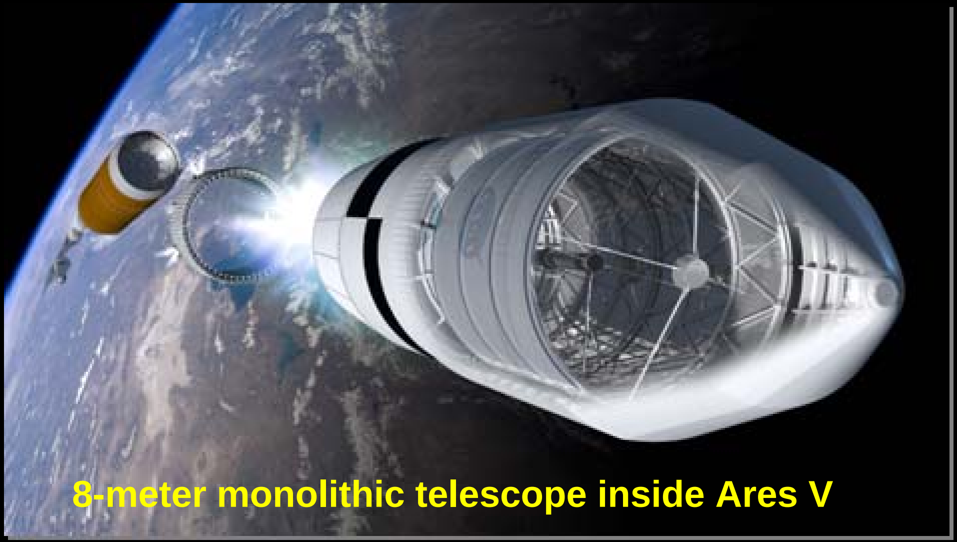


Big Questions in Cosmology that a Farside Radio Array may help to answer



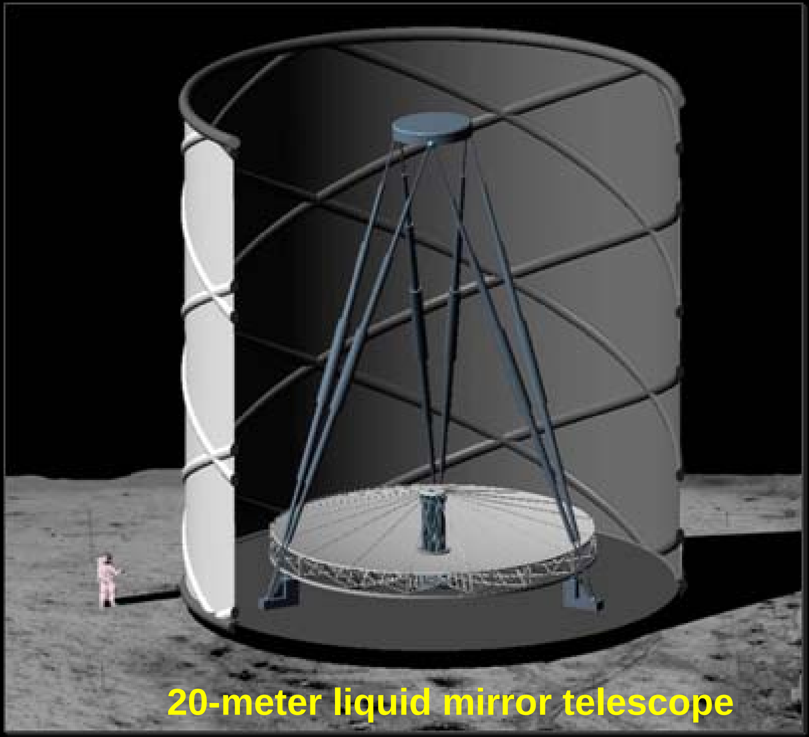
- What is Dark Energy and how does it evolve in time?
- Were there “exotic” heating mechanisms, such as Dark Matter decay, that occurred before the first stars formed?
- How did matter assemble into the first galaxies, stars, and black holes?

Other Possible Astrophysics Enabled by a Return to the Moon



8-meter monolithic telescope inside Ares V

Lunar Cosmic Ray Detector



20-meter liquid mirror telescope

Message from the Moon

Please come back!

I miss you!

LUNAR