

# Astronomy/Geology 5835

## Interdisciplinary Lunar Science Seminar

Class Syllabus & Website:

<http://lunar.colorado.edu/~jaburns/astr5835>



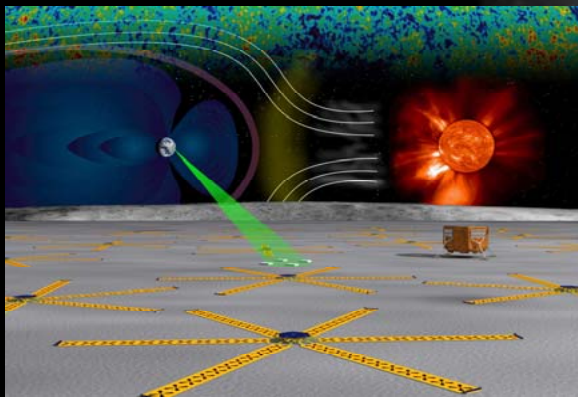
Science of the Moon



Science on the Moon



Science from the Moon





## *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.



NASA  
**LUNAR SCIENCE**  
INSTITUTE

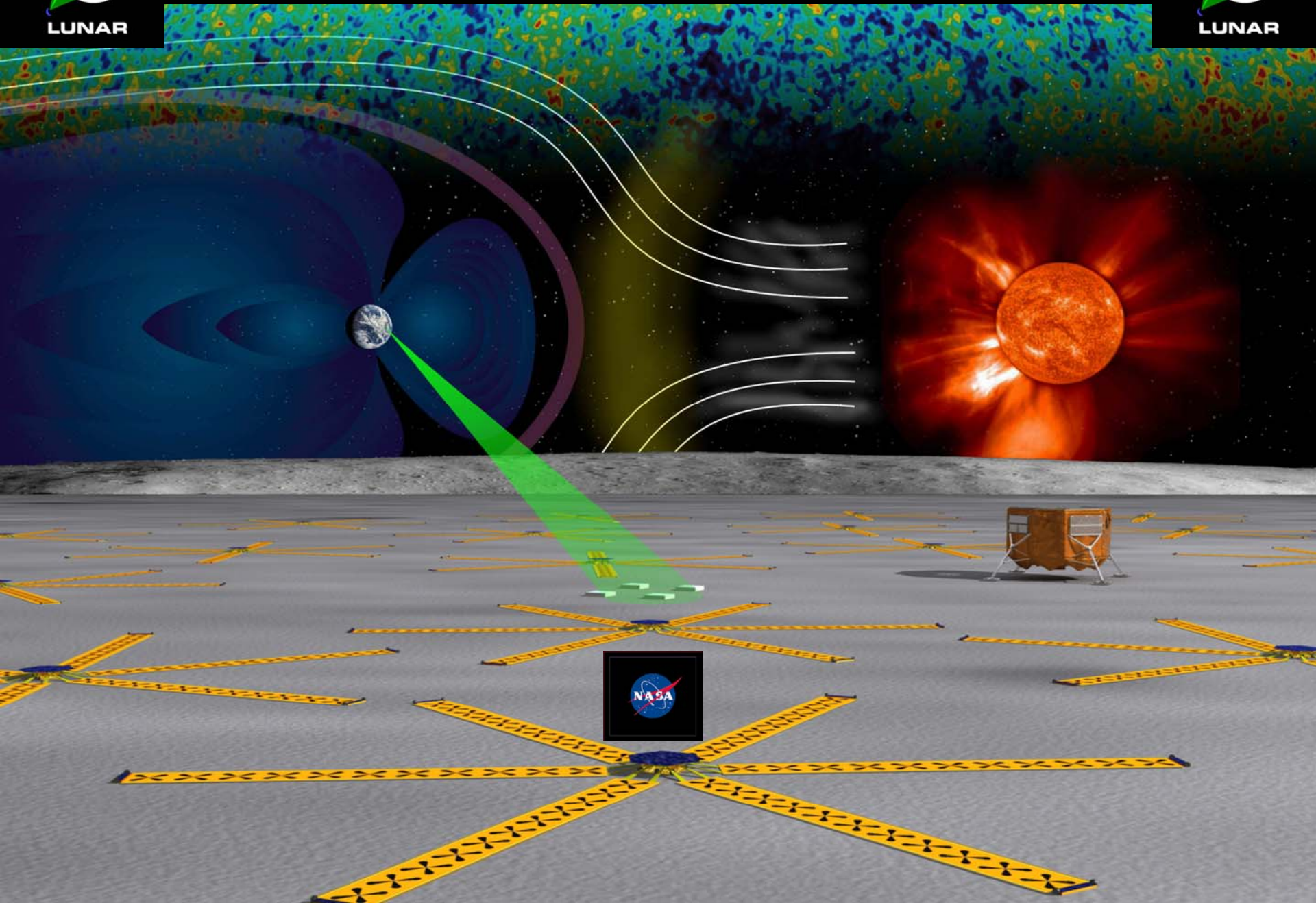


**Lunar University Network for  
Astrophysics Research (LUNAR)**





# Exploring the Cosmos from the Moon



# Gravitational Physics & Lunar Structure via Lunar Laser Ranging



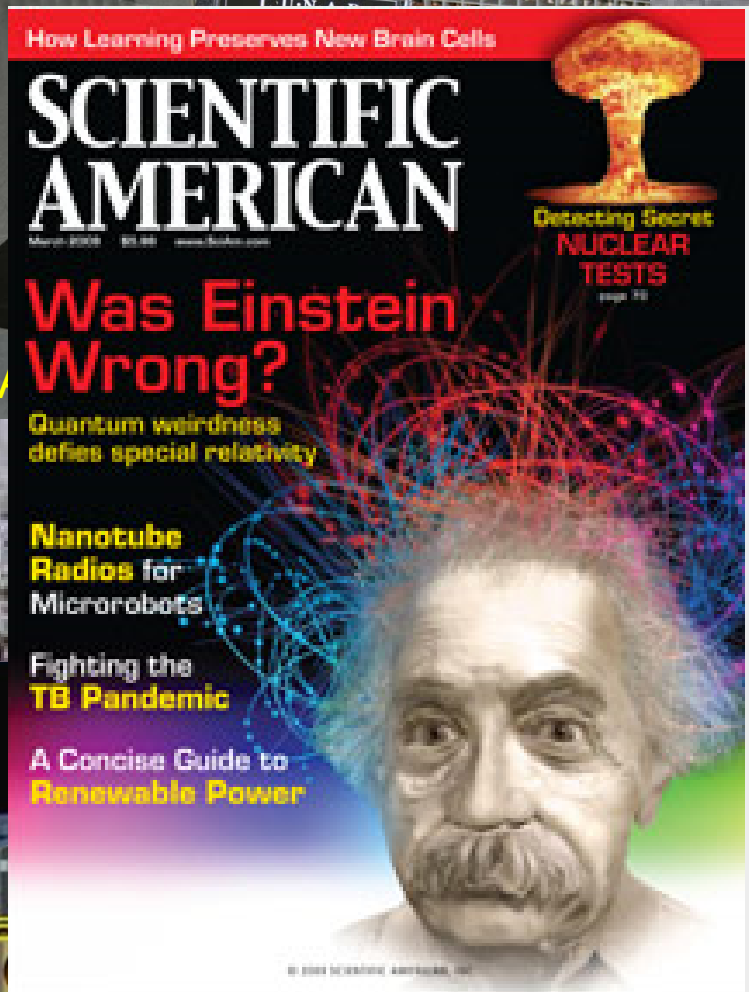
APOLLO = Apache Point Observatory Lunar Laser-ranging Operation



## Current Capabilities

- Accuracy  $\approx 1$  mm.
- Strong Equivalence principle  $\eta < 4 \times 10^{-4}$ .
- $\dot{G}/G < 6 \times 10^{-13}$  per year.
- Deviation from inverse-square law is  $< 3 \times 10^{-11}$  times strength of gravity at  $10^8$  m scales.

# Next-Generation Laser Retroreflector Array for the Moon

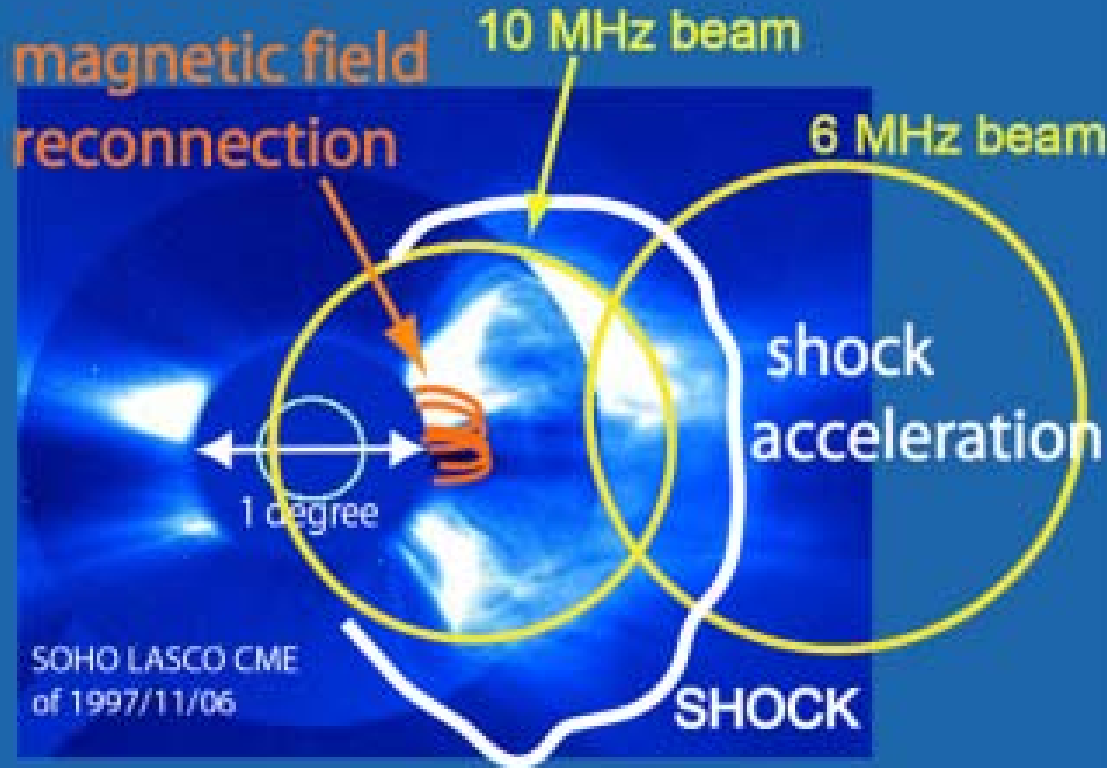


## *Fundamental Questions on Gravity:\**

- Does Dark Energy exist?
- Is the Equivalence Principle exact?
- Does the strength of gravity vary with space and time?
- Do extra dimensions or other new physics alter the inverse square law?

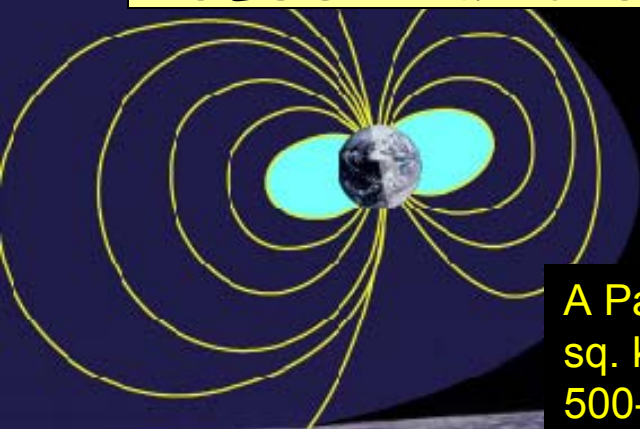
\*from Science White Papers submitted to Astro2010 & Planetary Sciences Decadal Surveys.

## Complex type III burst source



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

# ROLSS: Radio Observatory for Lunar Sortie Science

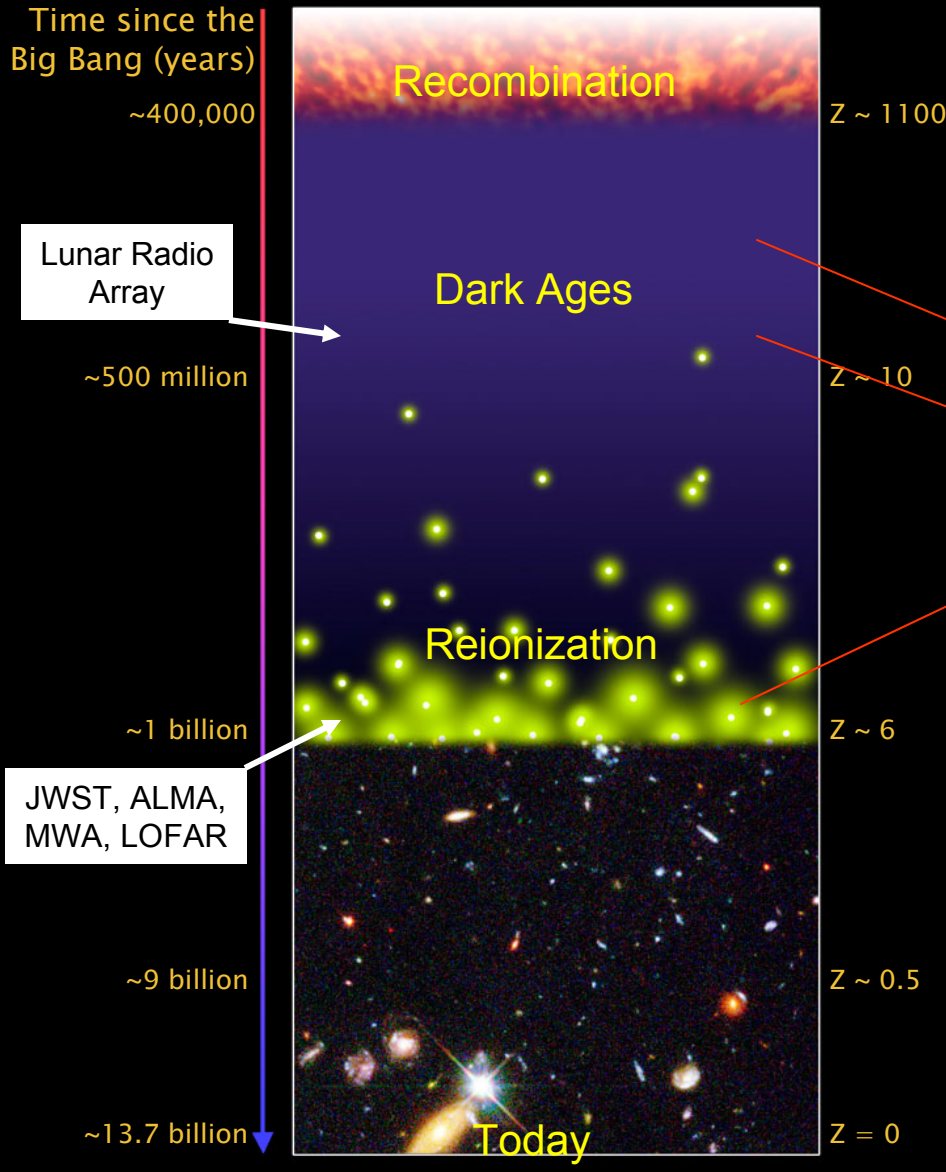


A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km). Operating at 1-10 MHz (30-300 m). Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.

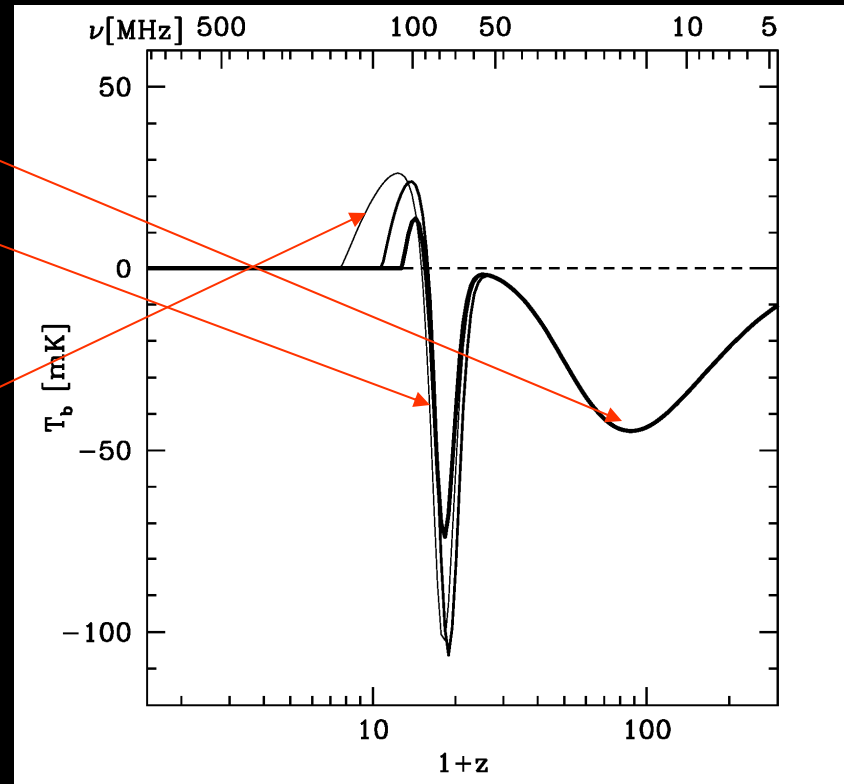
- Arms are thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).







## The Global (sky-averaged) HI Signal



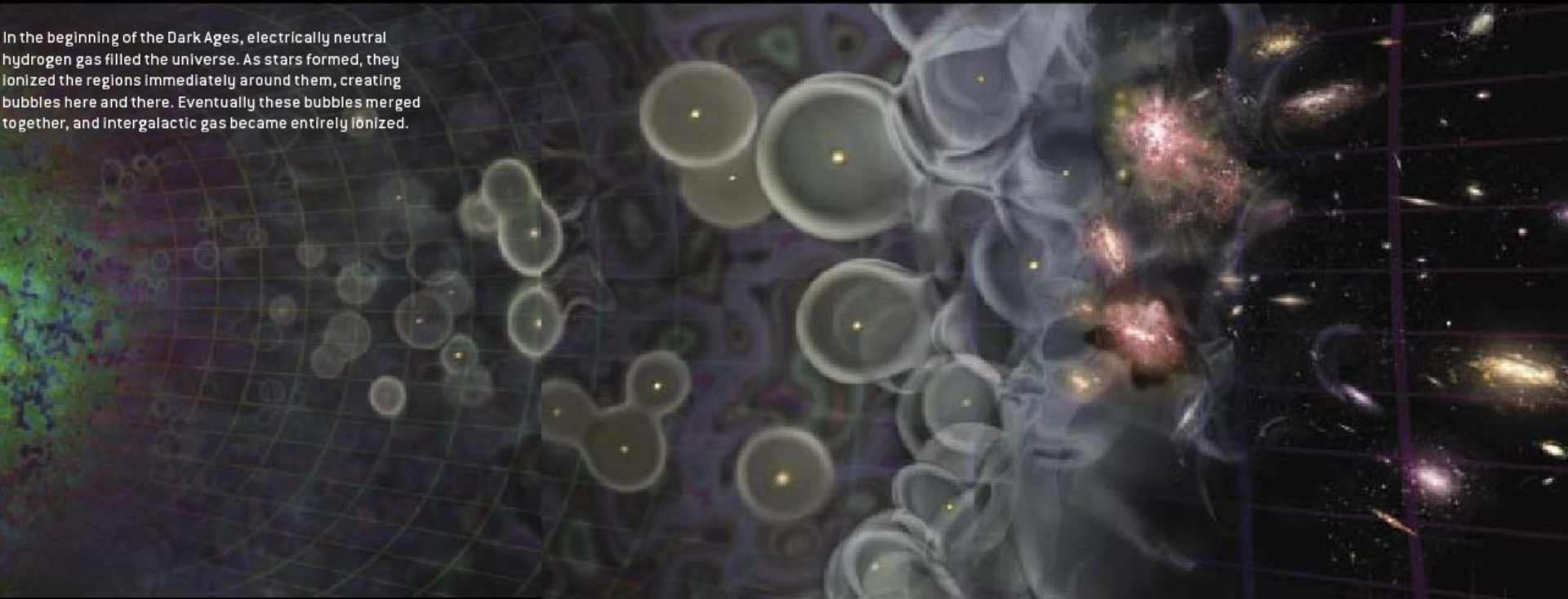
Pritchard & Loeb, 2008, Phys. Rev. D., 78, 3511.

**$21 (1+z) \text{ cm} = 1420/(1+z) \text{ MHz}$**   
 At  $z=10$ ,  $\lambda = 2.3 \text{ m}$  (130 MHz)  
 At  $z=50$ ,  $\lambda = 10.7 \text{ m}$  (30 MHz)

# 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:  
Width of frame:  
Observed wavelength:

210 million years  
2.4 million light-years  
4.1 meters

All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.

290 million years  
3.0 million light-years  
3.3 meters

Faint red patches show that the stars and quasars have begun to ionize the gas around them.

370 million years  
3.6 million light-years  
2.8 meters

These bubbles of ionized gas grow.

460 million years  
4.1 million light-years  
2.4 meters

New stars and quasars form and create their own bubbles.

540 million years  
4.6 million light-years  
2.1 meters

The bubbles are beginning to interconnect.

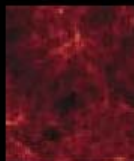
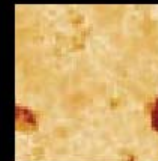
620 million years  
5.0 million light-years  
2.0 meters

The bubbles have merged and nearly taken over all of space.

710 million years  
5.5 million light-years  
1.8 meters

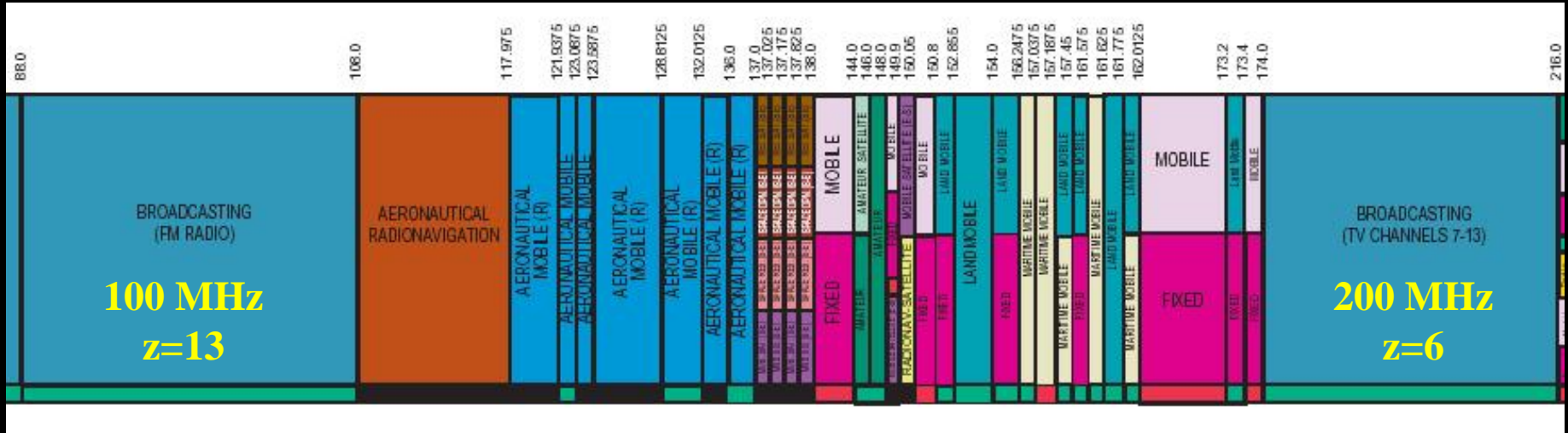
The only remaining neutral hydrogen is concentrated in galaxies.

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.

# Lunar Advantage: No Interference



# Destination: Moon!

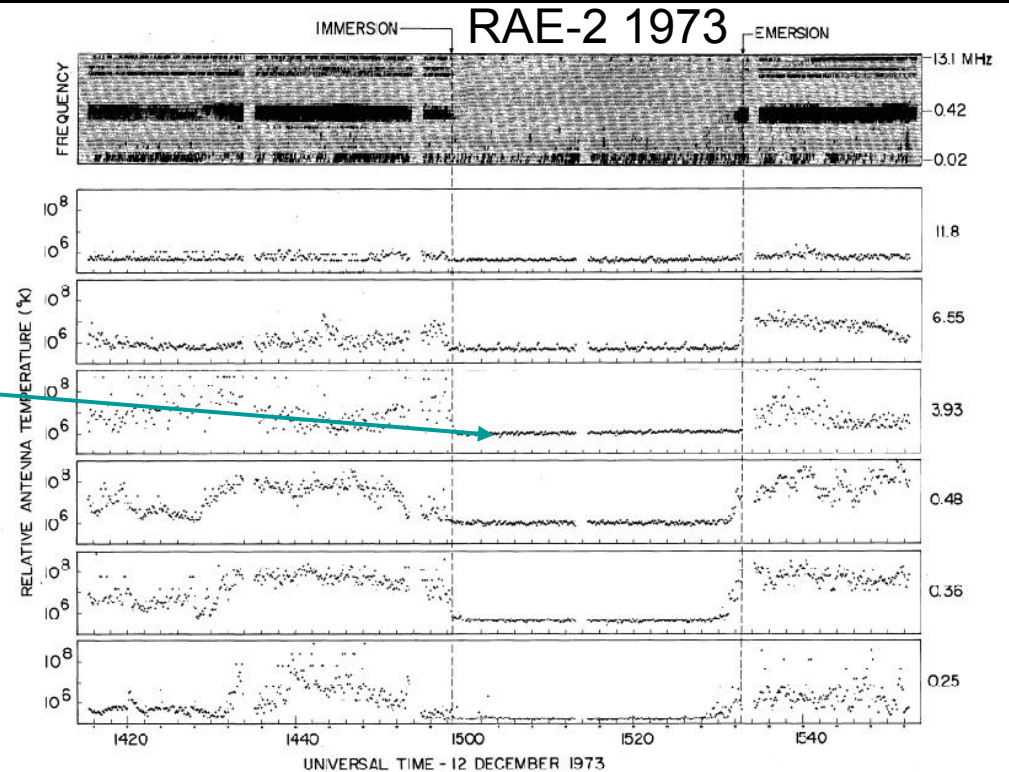


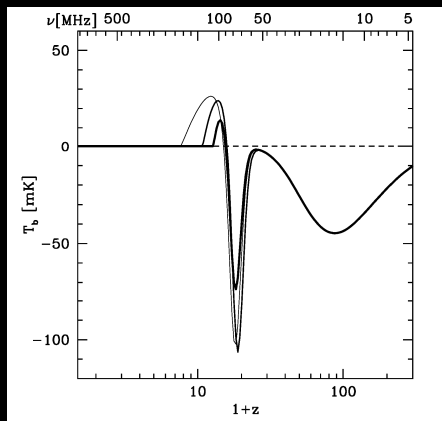
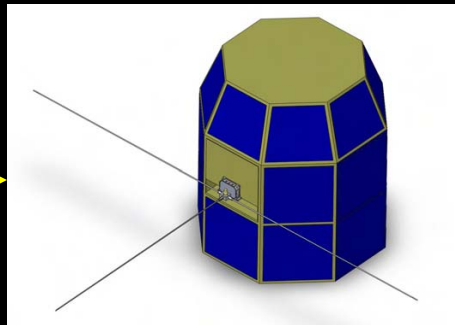
Fig. 5 Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur 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-Vouberg receiver local oscillator on occasions when both the receiver and the burst receiver are tuned to the same frequency.

# Roadmap to the Early Universe via Earth & the Moon

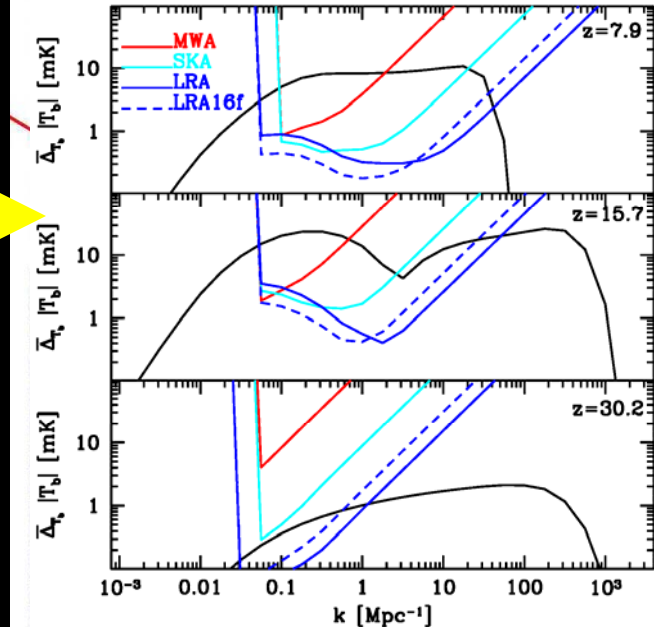
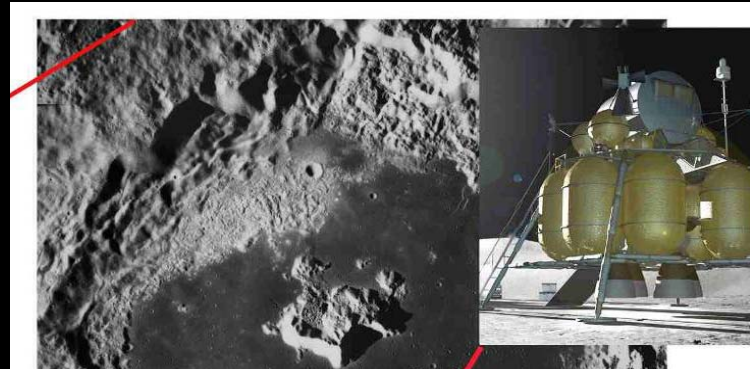
## Western Australia



## Lunar Orbit



## Lunar Farside

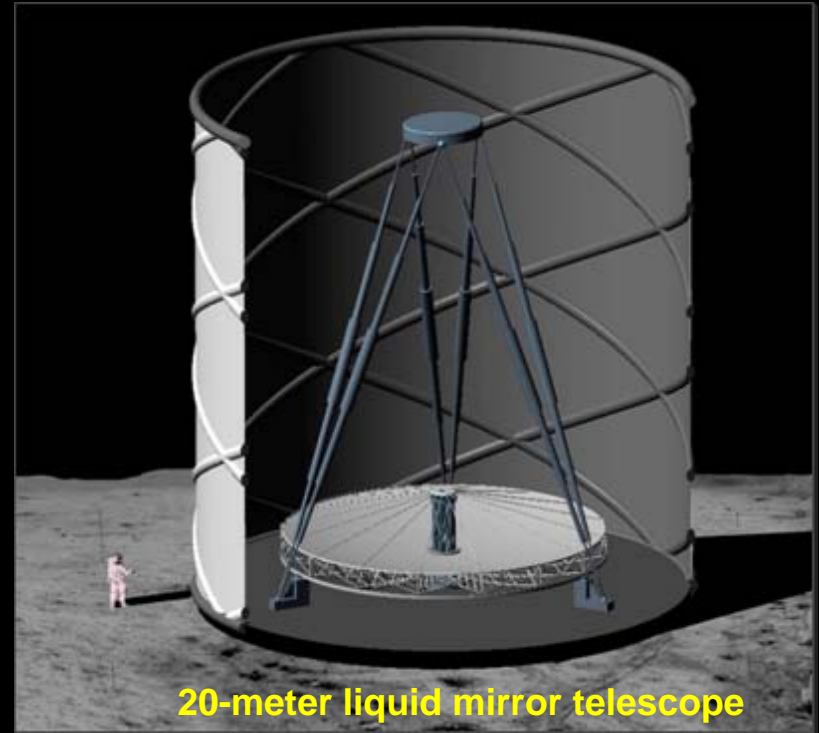


# Big Questions in Cosmology that a Farside Radio Array may help to answer

- What is the correct theory of inflation (deviations from Gaussianity in 21-cm power spectrum)?
- 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?



# Possible Other Astrophysics Enabled by a Return to the Moon



# Summary of LUNAR Components

- Gravitational Physics via Lunar Laser Ranging.
- Low Frequency Radio Heliophysics.
- Low Frequency Cosmology & Astrophysics.
- Assessment of other Astrophysics from the Moon.

