The Dark Ages Lunar Interferometer (DALI)

Joseph Lazio[1]

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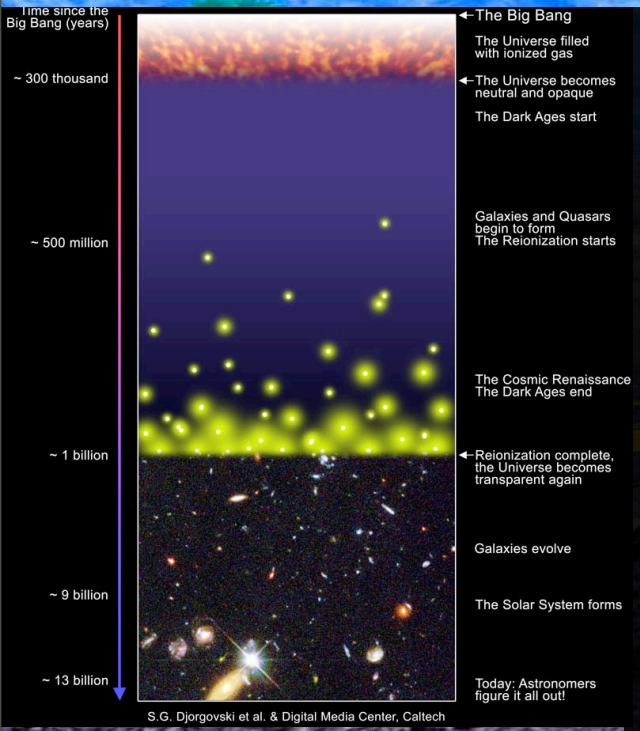
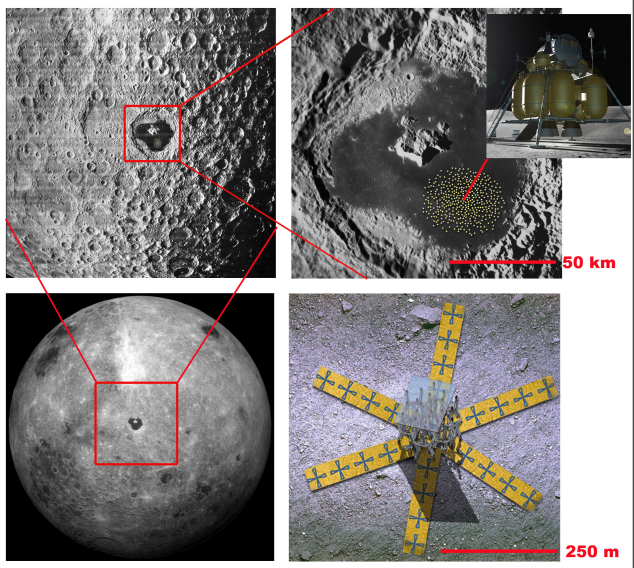
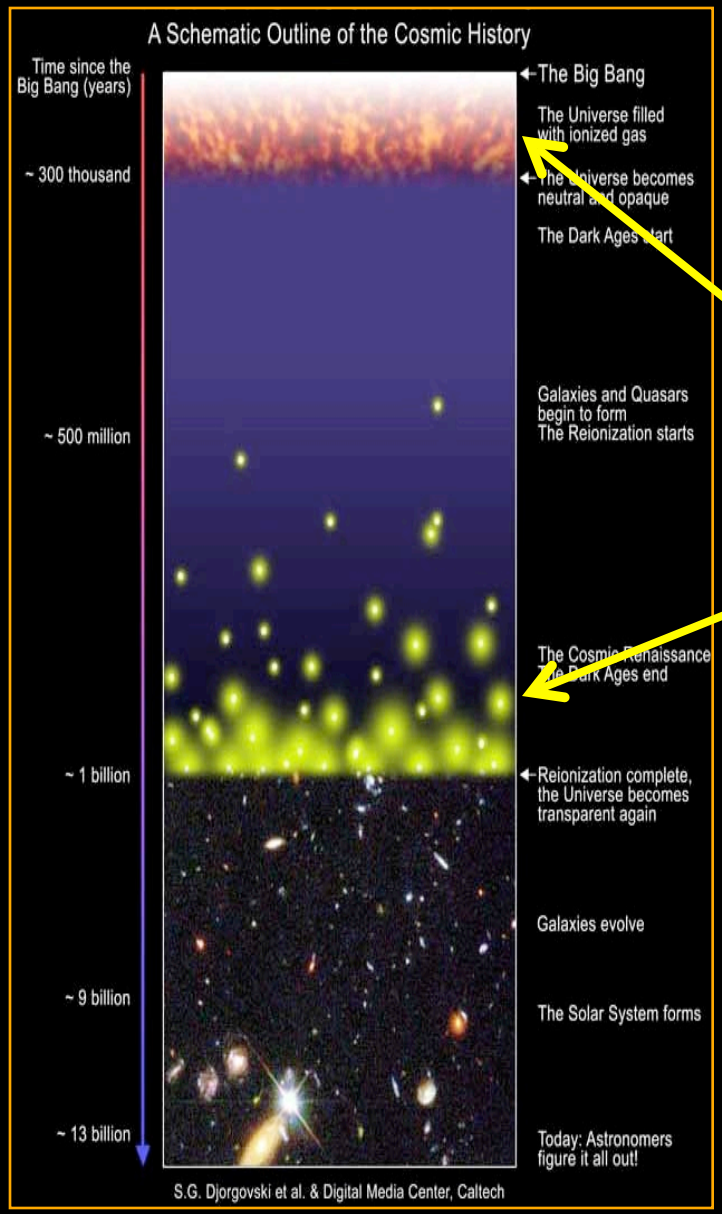


- Image the H I absorption signatures against the CMB
  - Significant science return — Potentially only way to probe this cosmic epoch
- Exploration Initiative opens avenue for exploitation of lunar far side
- Technology development required over next decade

Concept study funded by Astrophysics Mission Concept Studies program



Evolution of the Universe



Between recombination and the appearance of first luminous objects

- Recombination, $z \sim 1100$ (CMB)
- Epoch of Reionization, $z \sim 6$

- Most baryons in form of H I
- H I begins collapsing into dark matter-dominated, overdense regions

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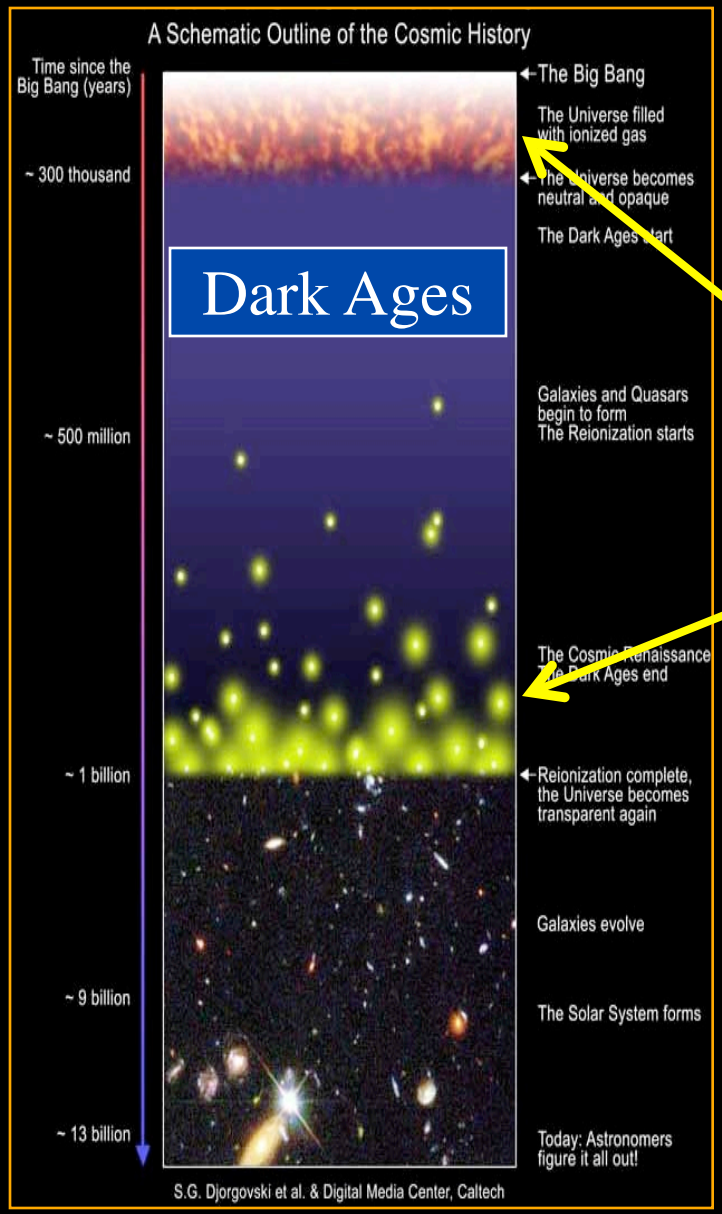

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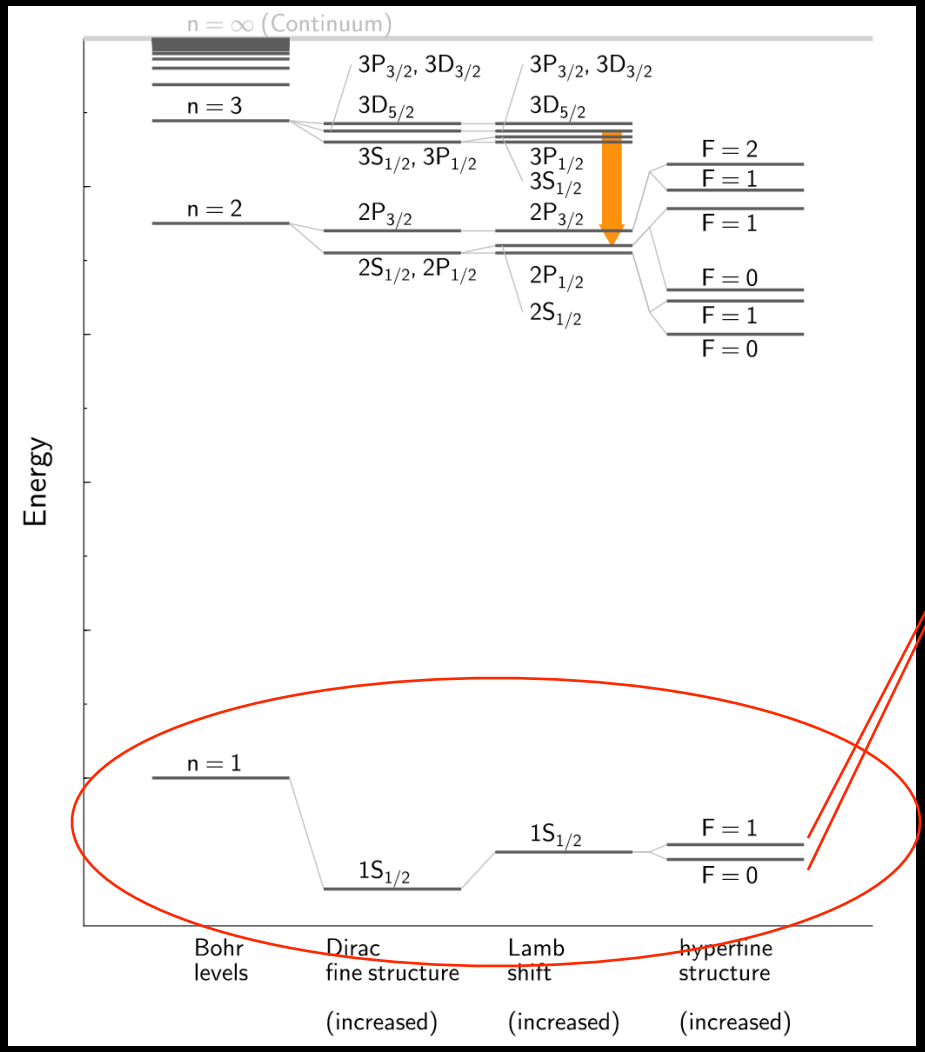
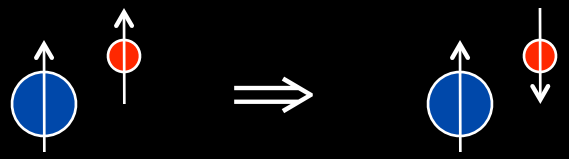
Hydrogen Atom





$n = 1$

$F = 1 \rightarrow 0$

$kT = h\nu = 5.8743253\ \mu eV$

$\nu = 1420.405752\ MHz$

$\lambda = 21\ cm$

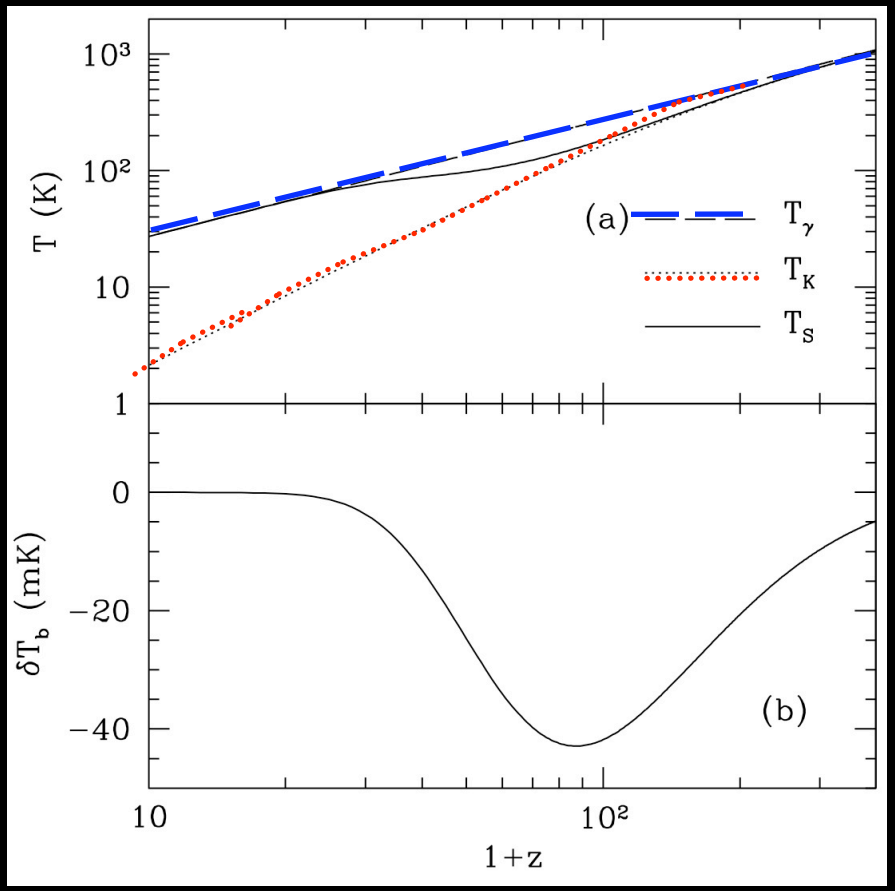
Evolution of the Universe

- **Dark Ages:** z ~ 30–200; IGM thermal evolution
- **First Stars:** *z* ~ 20–25?; heat the IGM via UV emission
- **First Black Holes:** *z* ~ 15–10?; heat the IGM via X-ray emission
- **A Quiet Era:** *z* ~ 10–12; may require *fine tuning*
- **Reionization:** 12 <~ *z* < 6 (SDSS Gunn-Peterson; WMAP)

(on-going ground-based work)

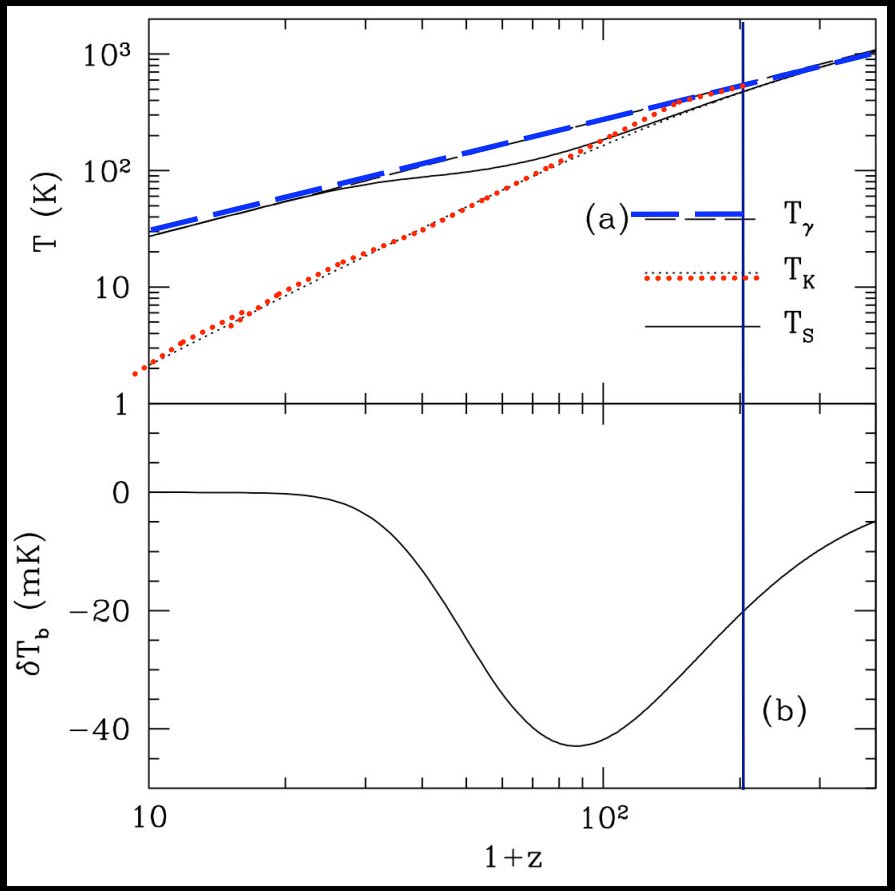
Murchison Widefield Array (MWA)

The Dark Ages



- Initially, H I gas temperature coupled to CMB temperature
  - Compton scattering between CMB photons and residual electrons
- Universal expansion decouples H I gas and CMB temperatures
  - $T_H \propto (1 + z)^2$
  - $T_{CMB} \propto (1 + z)$
- Collisions keep H I gas and spin temperatures coupled
- H I spin temperature *lower* than CMB
  - Absorption signature *against* CMB
- $z \sim 30$–200
  - $\nu \sim 10$–50 MHz

The Dark Ages



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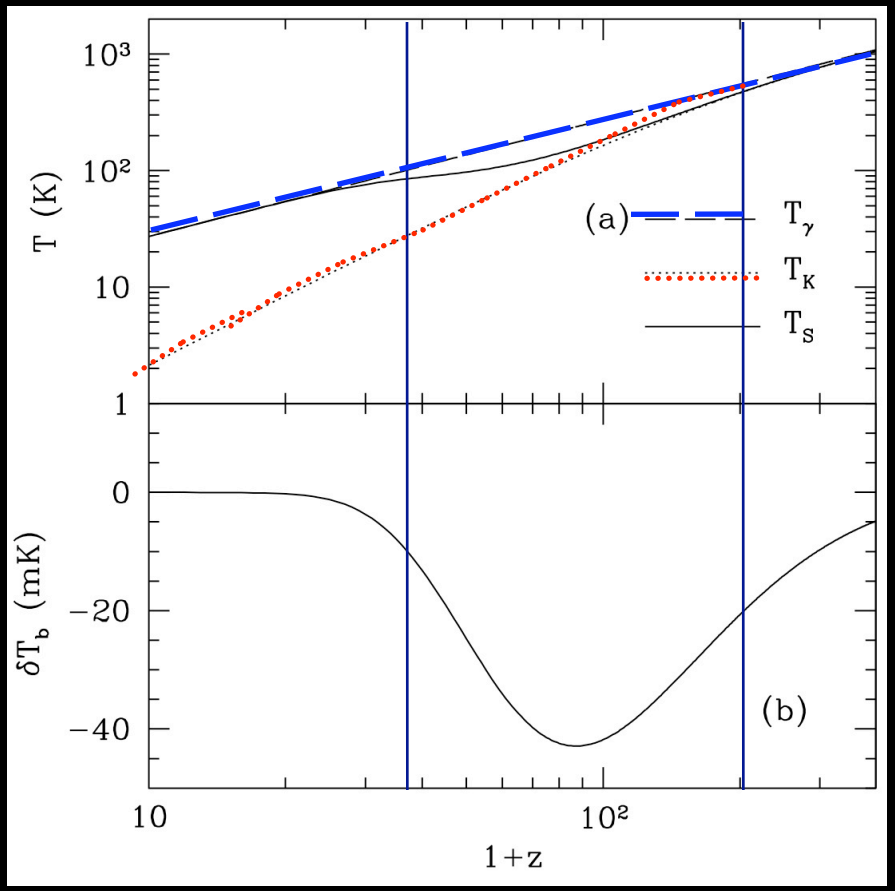

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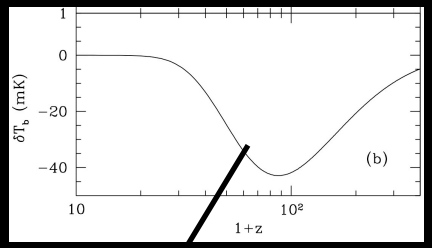
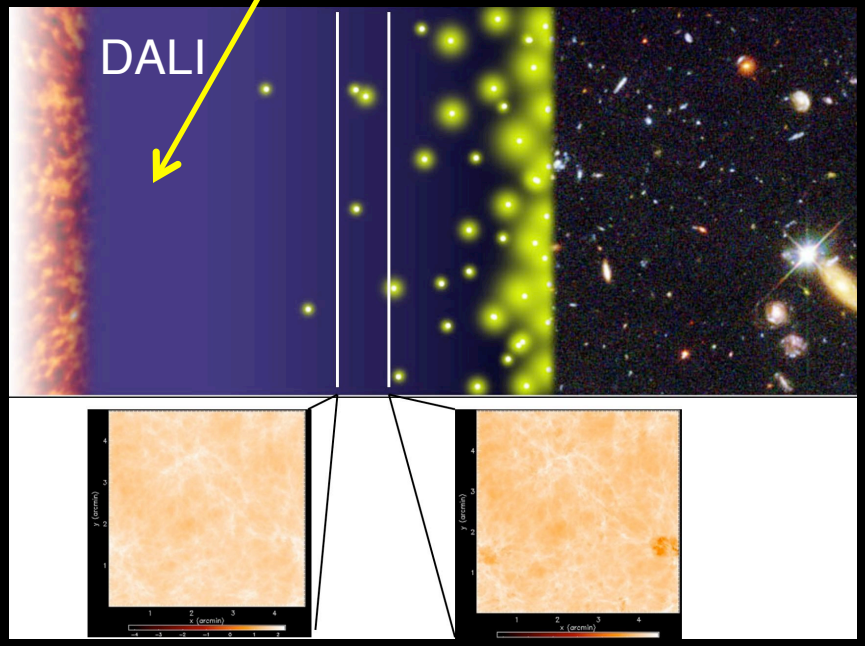
Dark Ages Lunar Interferometer

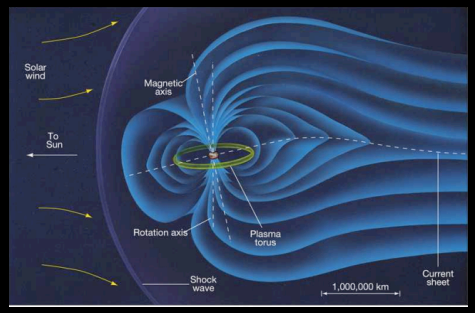




Spectroscopically image the H I absorption against the CMB

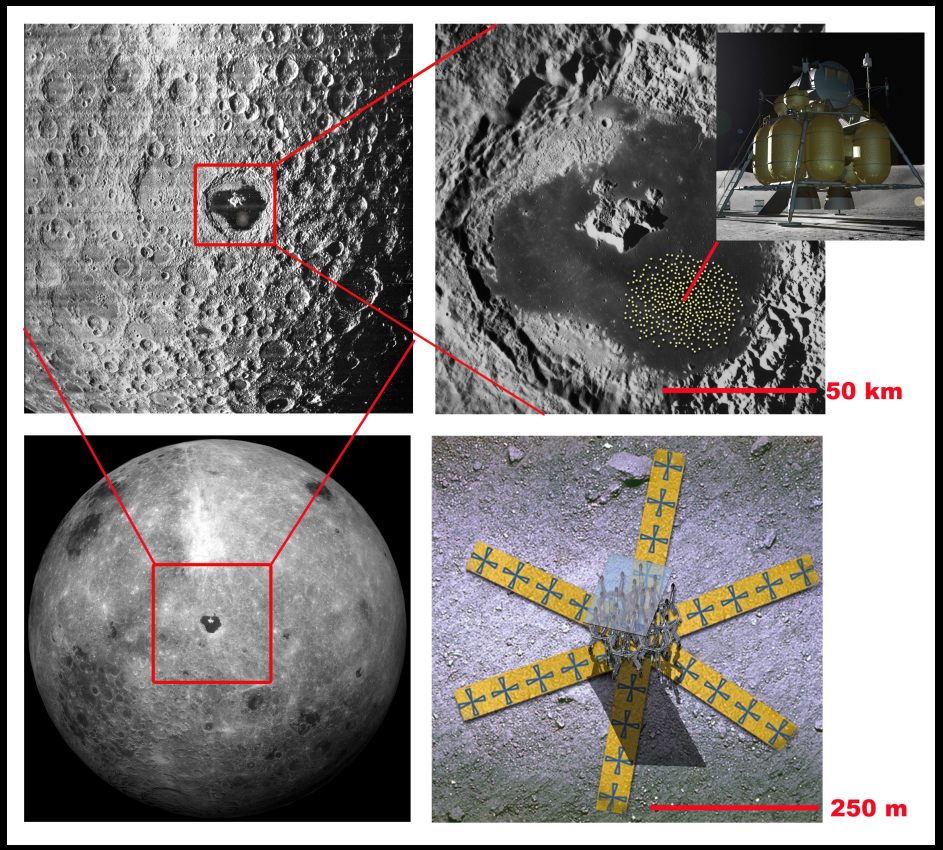
Form 3-D image of evolving Universe

- Likely to be the only means of *directly* probing this cosmic epoch.
  - Post-CMB experiments (WMAP, Planck, …)
  - Pre-Epoch of Reionization
    - JWST
    - ALMA
    - MWA, LOFAR, PAPER, …
- Secondary science
  - Magnetospheric emissions from extrasolar planets



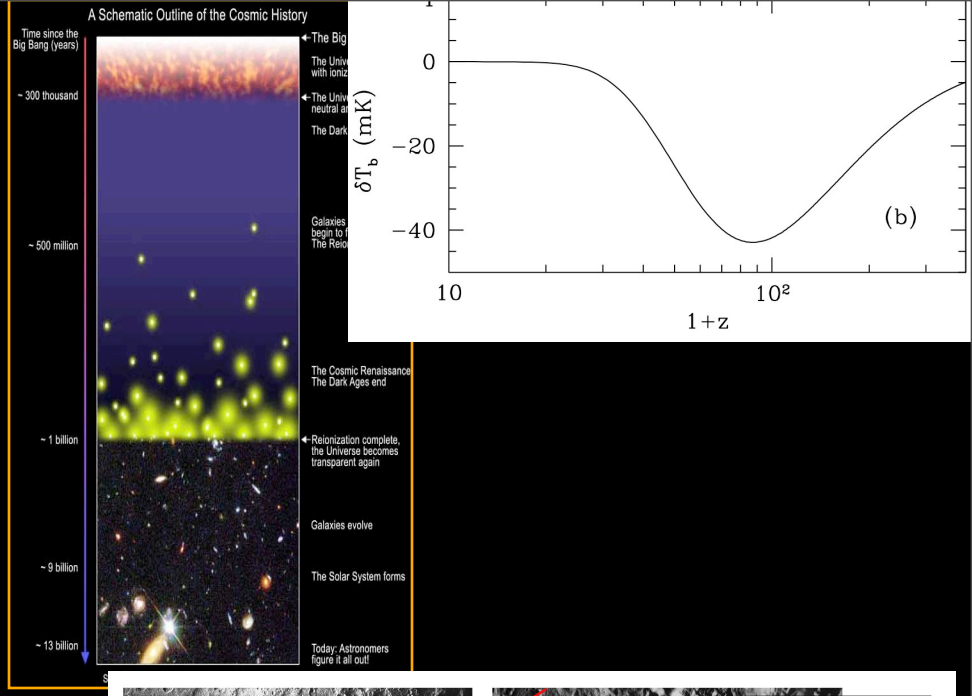
DALI Baseline Mission

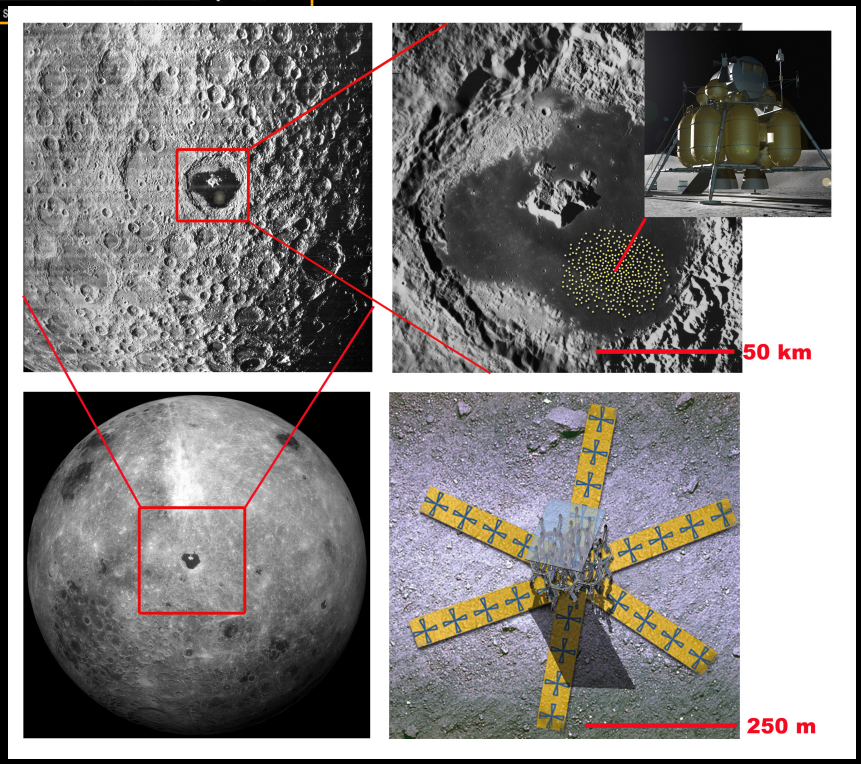
- Antennas grouped in “stations”
- 1000 stations of 100 antennas
- Stations deployed via rovers
- Signals from stations transmitted via laser links to correlator
- Operations:
  - Launch on Ares V
  - Tsiolkovsky crater
  - Observations during lunar night
  - Data stored at stations, transmitted to correlator during daylight
  - Relay satellite for downlink to Earth



Why the Moon's Far Side?

- Sun
  - Only nighttime observations sufficient
- Radio frequency interference
  - No place on Earth dark at these frequencies
- Ionosphere
  - Significant effects already seen at 74 MHz ($z \sim 20$)

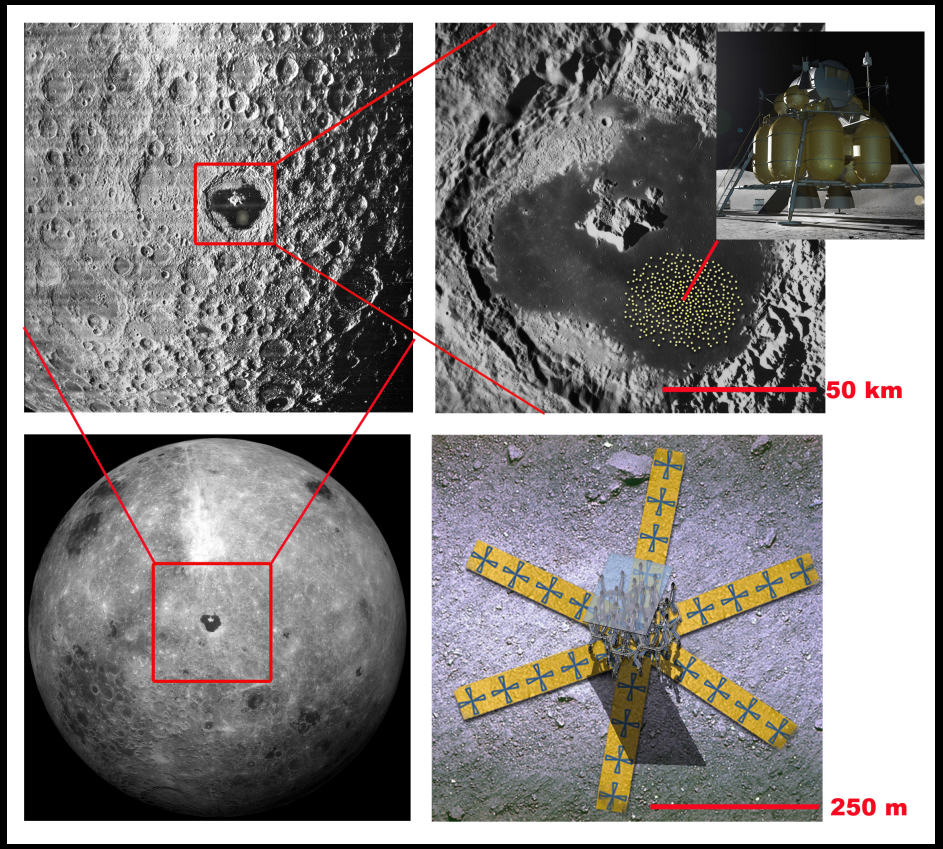




DALI

Key subsystems

- Antennas
- Receivers/beamformers
  - No significant technology development (long heritage of HF/VHF receivers)
- Data storage
  - ~ 500 Tb per lunar night
- Rover deploys a station
- Data transmission
  - Lunar laser links
- Correlator
  - 1000 stations, *but* **small** bandwidth (~ MHz)
- Relay satellite downlink
  - ~ 2 Gb/s downlink
- Ground operations station



Concept study funded by Astrophysics Mission Concept Studies program

Antennas

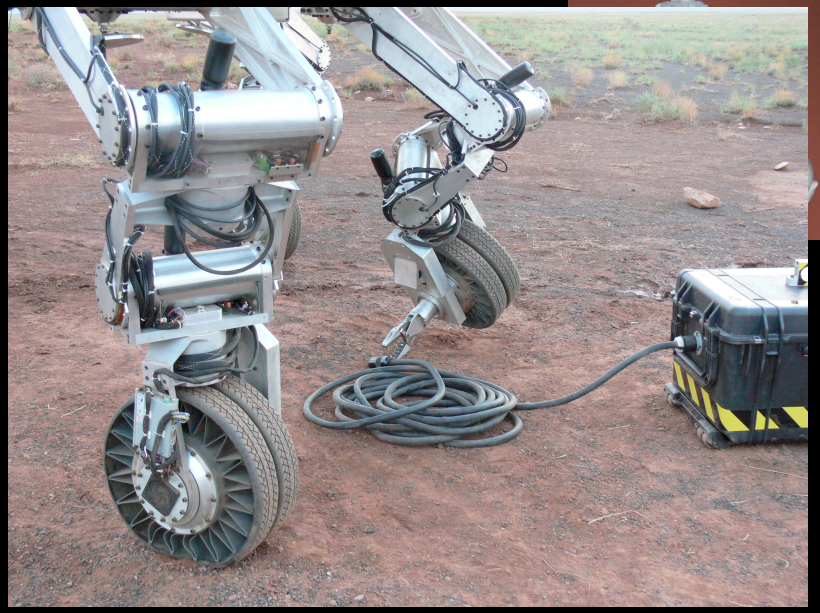
- Electrically short dipoles deposited on polyimide film.
- Polyimide film has long history of spacecraft applications.
- On-going work to test polyimide film in lunar conditions and electrical properties.
  - NASA/GSFC
  - U. Colorado
- Significant mass budget!

  Use of heavy-lift vehicle

Polyimide film (courtesy of Mantech SRS)

Rovers

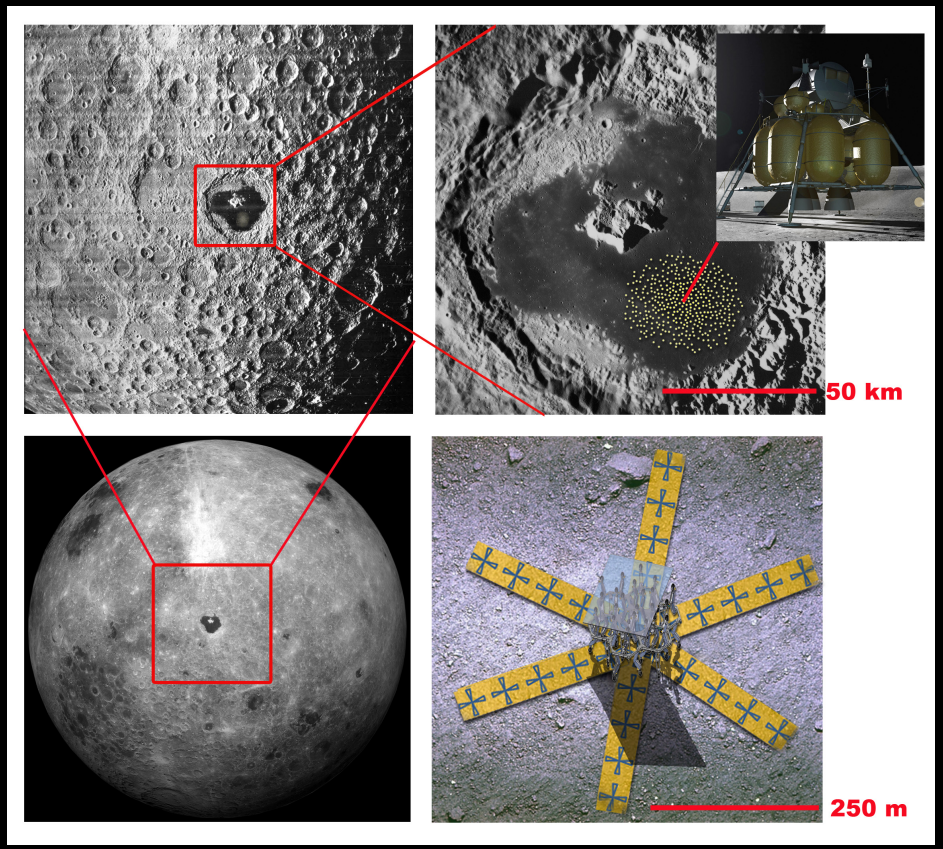
- Rover unrolls 3 polyimide film rolls
- Each roll has ~ 30 antennas
- Rover then serves as receiver/beamforming hub
- Significant rover heritage



JPL ATHLETE rover

Opportunity @ Mars

Ares V
& Constellation System



- Mass budget demands heavy-lift vehicle
  - Antennas/station
  - Rovers
  - Power
- Lander (Altair) — *cargo*

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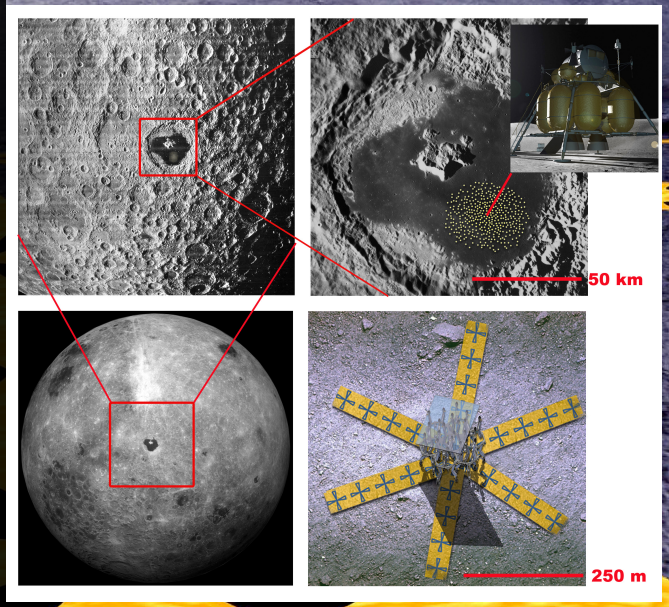
  - Significant science return — Potentially only way to probe this cosmic epoch
- Constellation system opens avenue for exploitation of lunar far side
- Technology development required over next decade to realize
  - Concept study funded under Astrophysics

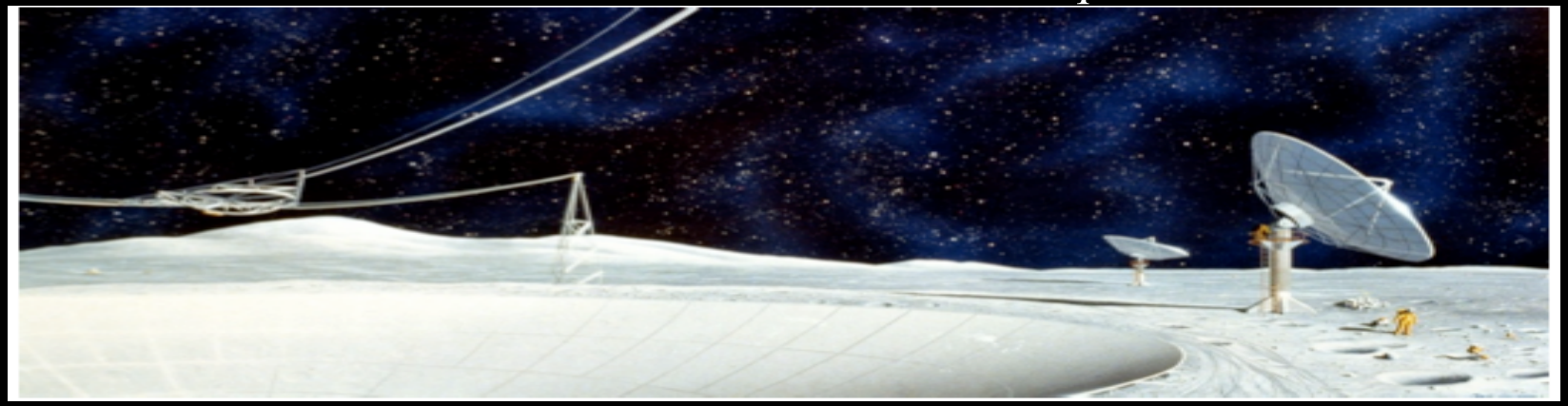


FINITO

Lunar Radio Telescope

- Not a new idea!
- First proposals *pre-date* Apollo missions
  - Research Program on Radio Astronomy and Plasma for Apollo Applications Program Lunar Surface Missions: Final Report 1966, North American Aviation Inc.
  - Greiner, J. M. 1967, "Utilization of Crater Reflectors for Lunar Radio Astronomy," Working Group on Extraterrestrial Resources
- Far side of Moon long recognized as unique astronomical platform

  International Telecommunications Union radio quiet zone



Ground-based Telescopes

Explicitly targeting detection of the H I signal from the Epoch of Reionization (end of the Dark Ages)

- 80–240 MHz ($z \sim 5$–15)
- Located in one of the most radio-quiet places on the planet: Western Australia
- Initial observational tests in progress

Murchison Widefield Array (MWA)

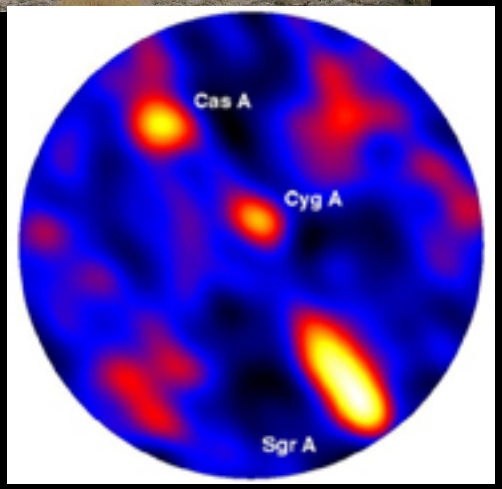
LOw Frequency ARray (LOFAR)

Explicitly targeting detection of the H I signal from the EoR

- Both high (120–240 MHz) and low (30–80 MHz) bands
- Located in one of the most radio-active places on the planet: Northern Europe
- Initial construction and test observations in progress

Ground-based Long Wavelength Array (LWA)

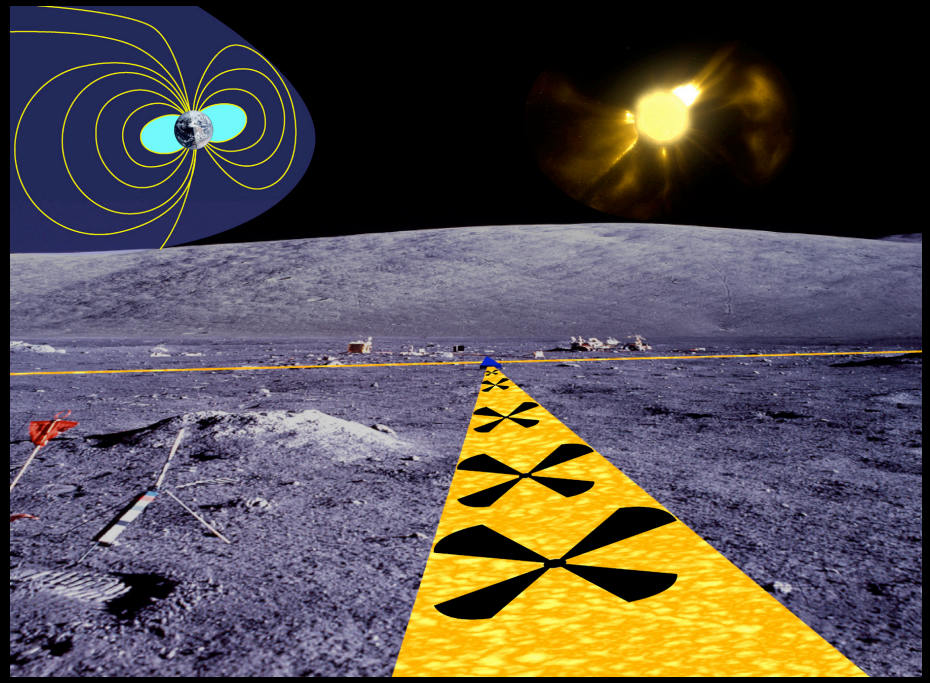
- Aim is to explore high-resolution, long-wavelength sky for first time …
- *But*, frequency range well-matched to Dark Ages exploration as well
  - 20–80 MHz
  - $z \sim 15$–70
- Located in a reasonably radio-quiet place on the planet: New Mexico, centered on VLA site



Radio Observatory for Lunar Sortie Science (ROLSS)

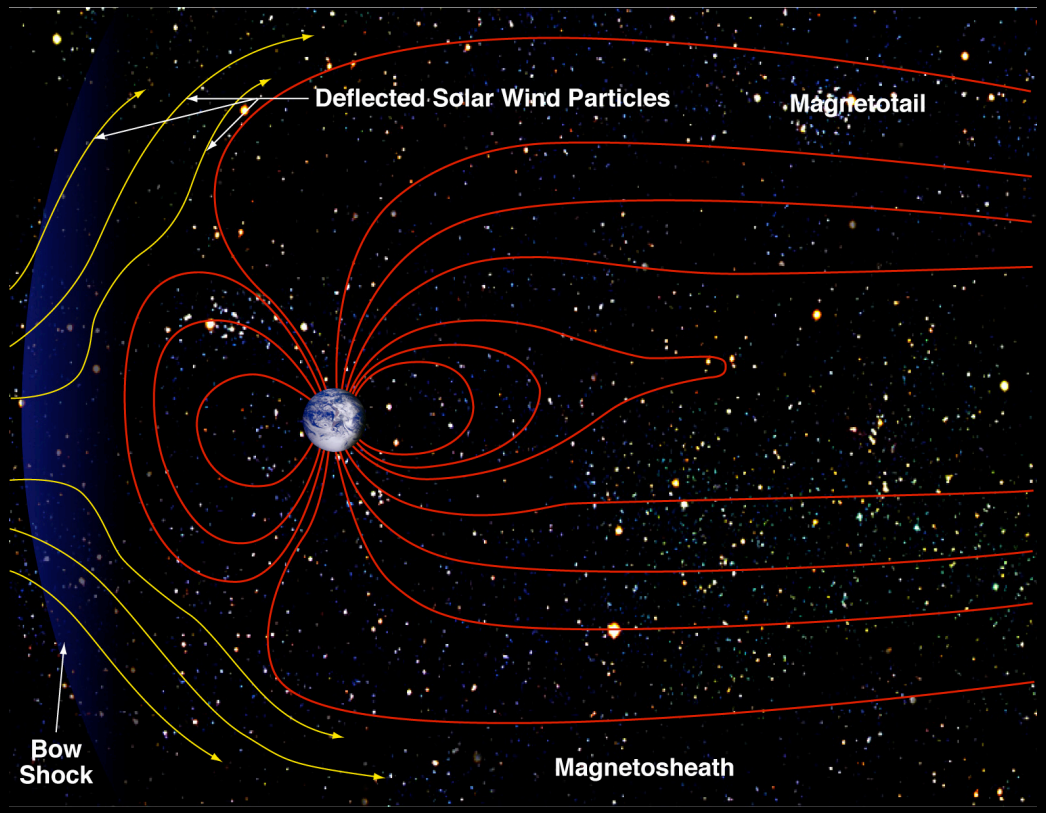
Long-wavelength interferometer on the Moon's surface

- Key science
  - Particle acceleration
  - Lunar ionosphere
  - **Pathfinder to larger arrays**
- Technical description
  - 30–300 m wavelength (1–10 MHz)
  - Antennas deposited on polyimide
  - Deploy by unrolling – 500m arms
  - 3-arm interferometer
  - 2° resolution (@ 30 m)
  - Order of magnitude improvement in



Concept study in progress, funded by Lunar Sortie Science Opportunity program.

Secondary Science
Extrasolar Planets



- Planetary magnetic field immersed in solar wind.
- Solar wind is high-speed plasma with embedded magnetic field.
- Pressure from solar wind impacts and deforms planetary magnetic field.
- Magnetosphere

  Large objects, e.g., Jovian magnetosphere is 5x diameter of full Moon

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Extrasolar Planets

- Jupiter (and other giant planets) produce intense radio emission below 40 MHz.

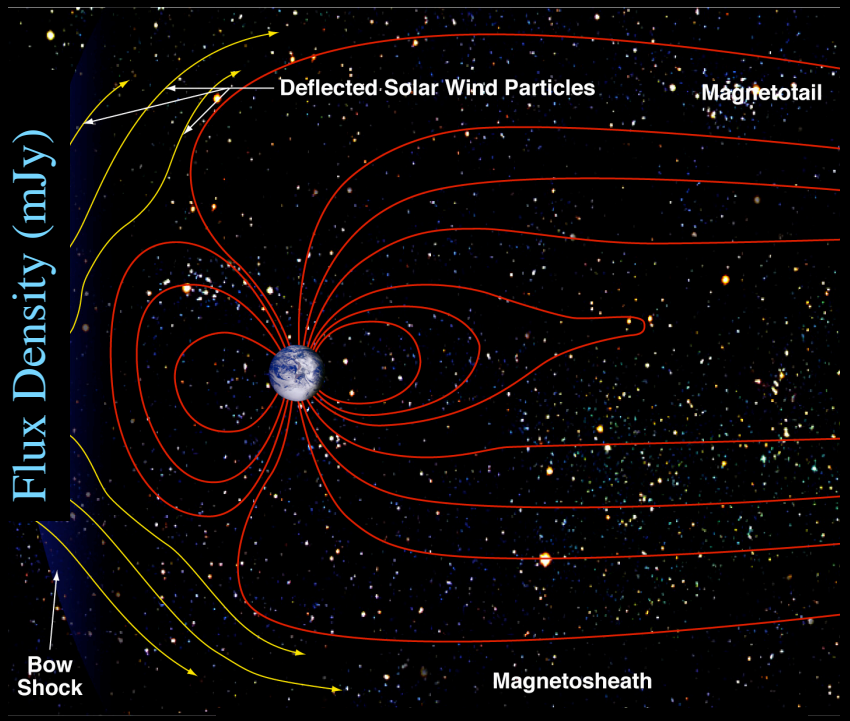
  Earth below 1 MHz

- ~ 200 extrasolar giant planets known.

  What will be the solar neighborhood census in 2020?

- Do they produce radio emission?
- Planetary magnetosphere may be important for habitability.

➢Of the solar system planets, only Jupiter can be detected from the ground.



(Lazio et al. 2004)

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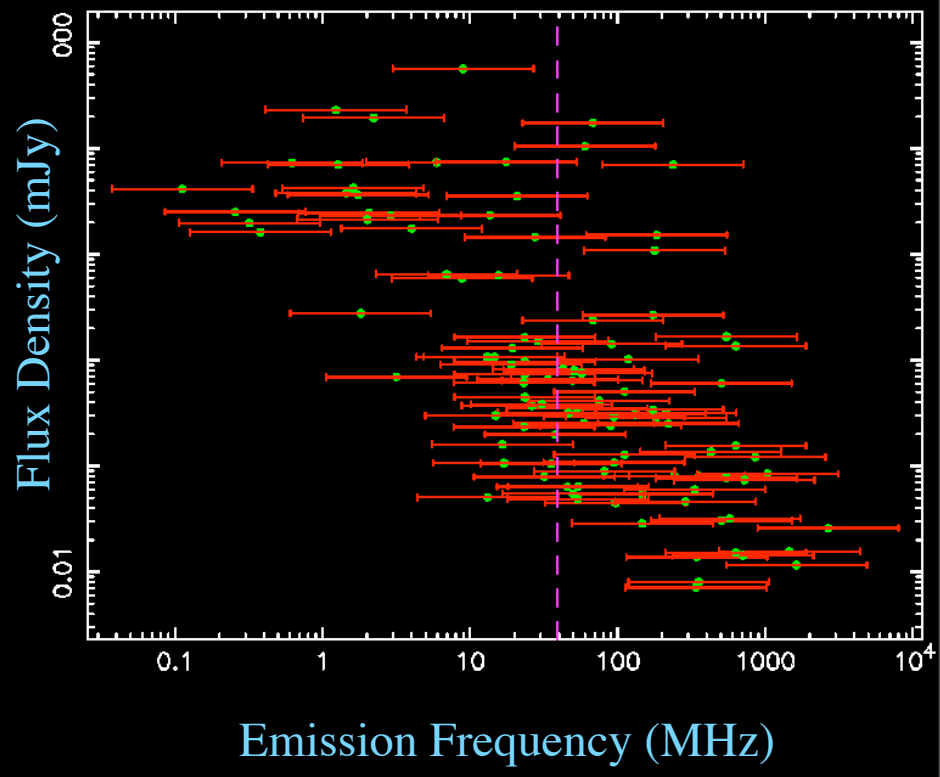
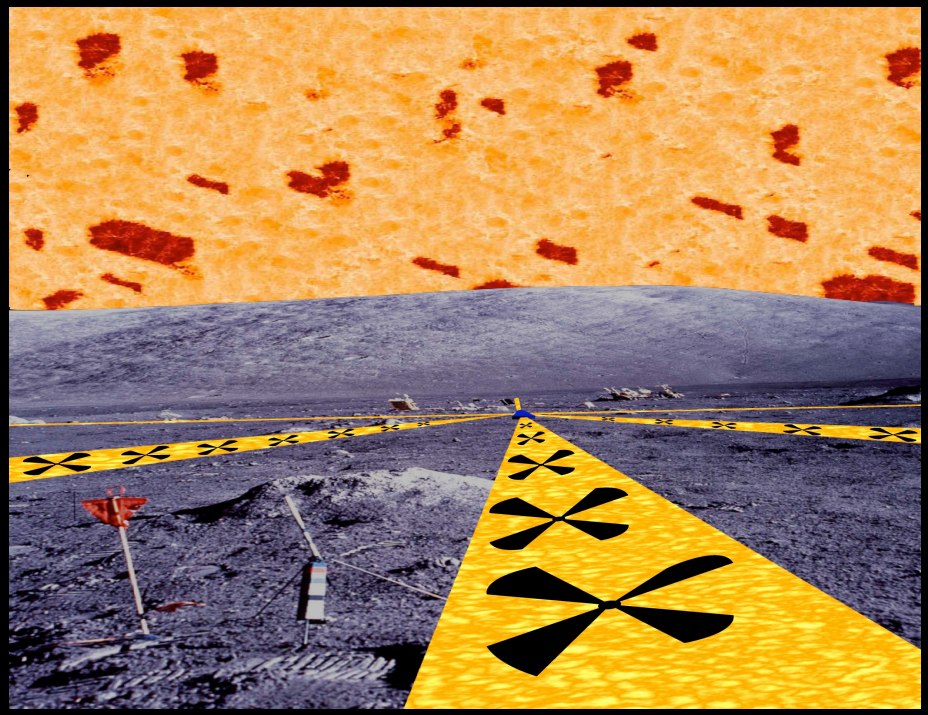


(Lazio et al. 2004)

Lunar Radio Telescopes

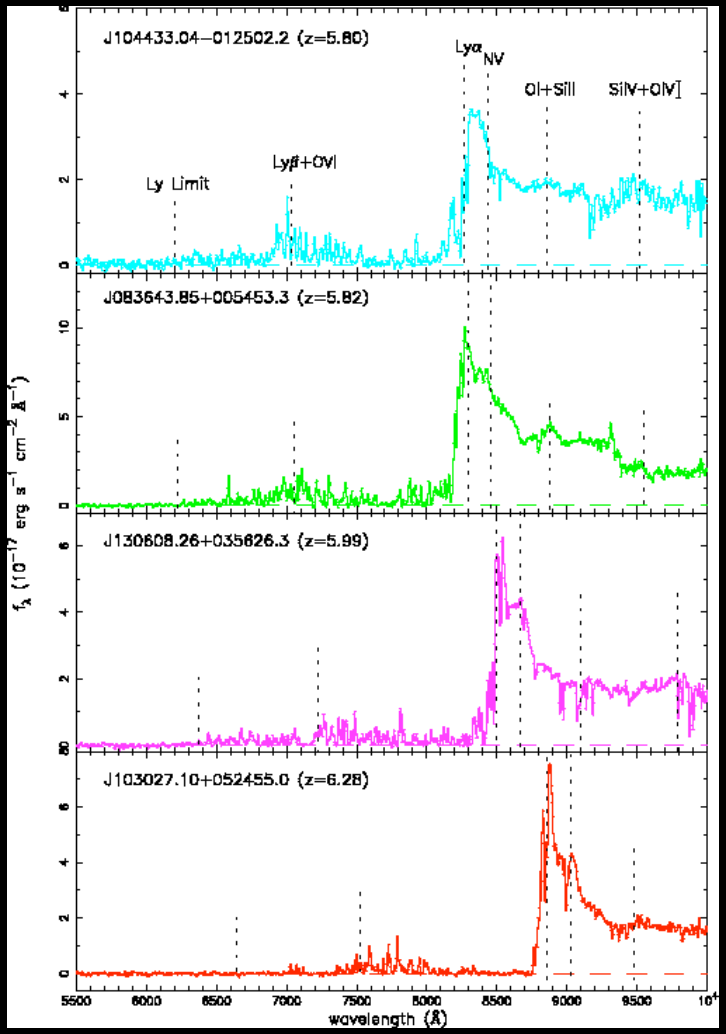
- Long history
  - Suggestions pre-date Apollo missions
  - Concept developed in the 1980s, 1990s
  - Attraction of the Moon
    - Shielding of Earth, and Sun, no radio emissions on far side
    - No permanent ionosphere
- Compelling science today: Dark Ages



Epoch of Reionization: $z \approx 6$ (H I at 200 MHz)

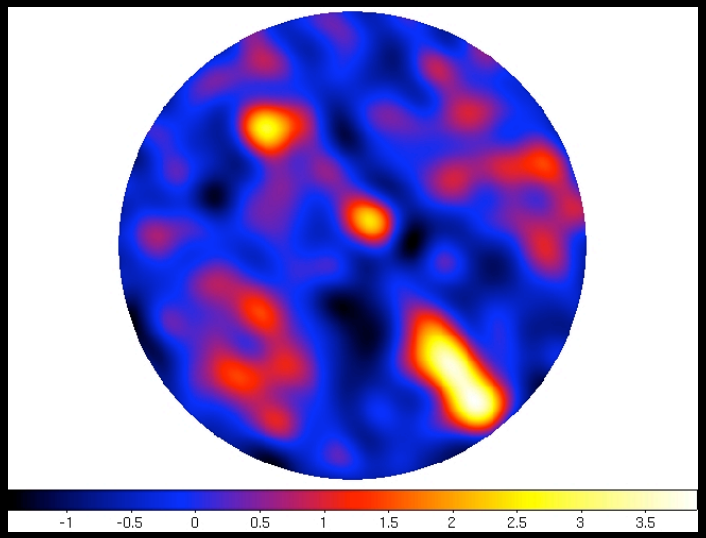
Universe made rapid transition from largely neutral to largely ionized

- Appears as Gunn-Peterson trough in high-z quasars
- Also detectable by highly-redshifted 21 cm H I line?

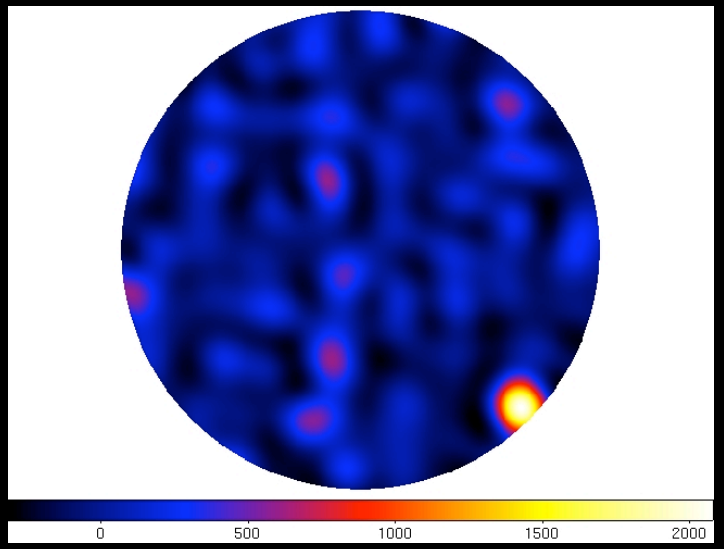


Becker et al. (2001)

Solar Radio Emissions



Sky at 74 MHz as seen by Long Wavelength Demonstrator Array

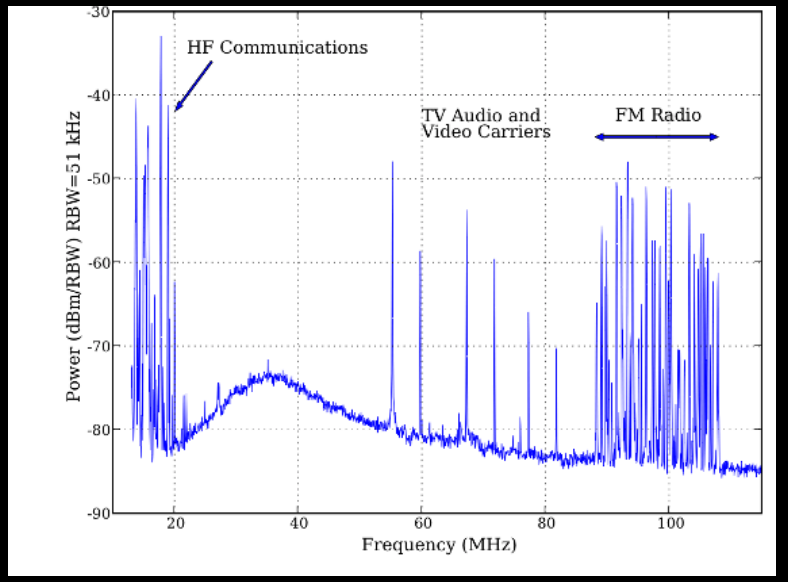


Solar flare observed by Long Wavelength Demonstrator Array

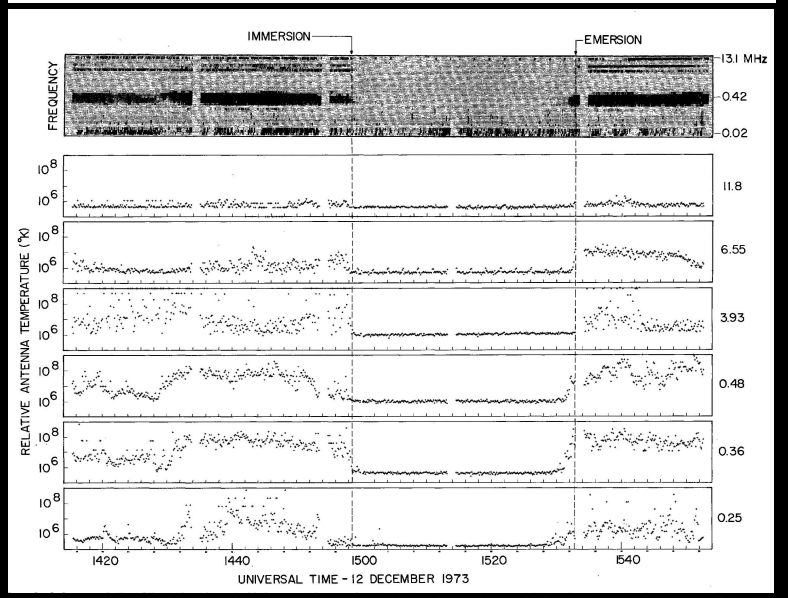
- Sun is extremely strong radio source, particularly during flares.
- Only mitigation is nighttime observations.

Radio Frequency Interference (RFI)

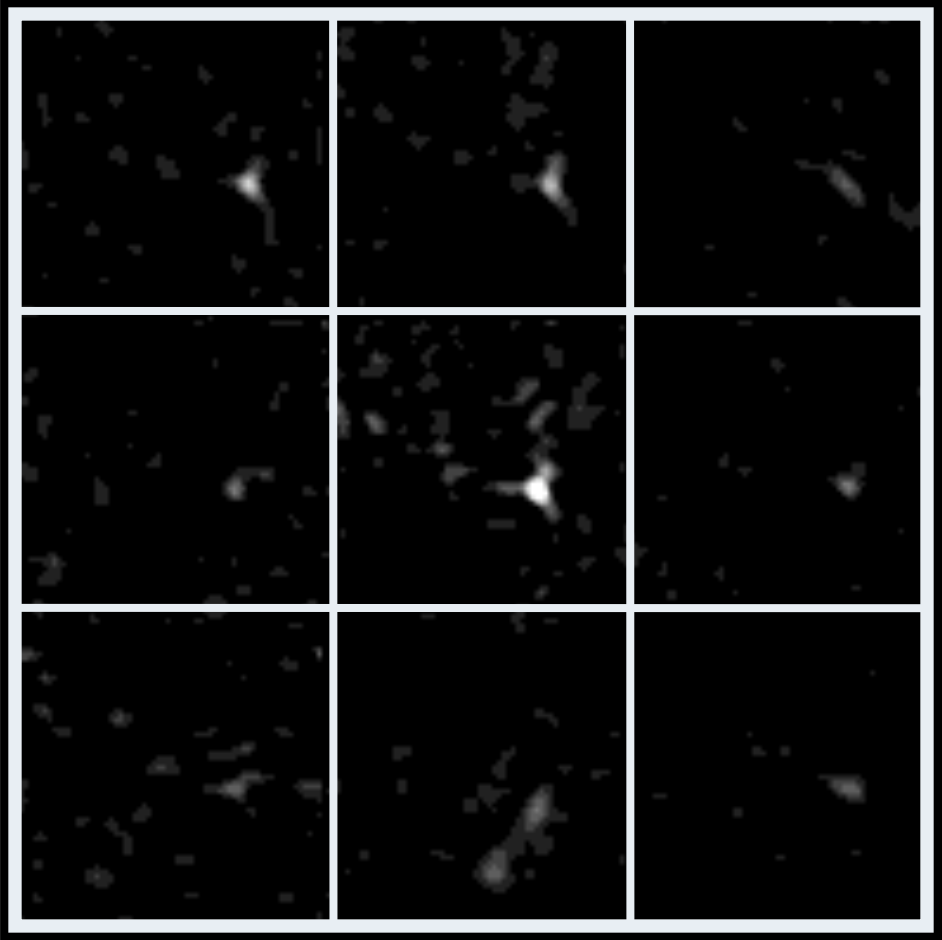
- Even a relatively quiet site like the VLA has significant interference
  - HF communications seen internationally



- Far side of the Moon is *the* darkest place in the inner solar system for long-wavelength astronomical observations



Ionospheric Effects



- Ionosphere significant even at 74 MHz!
  - $z \sim 20$
- Opaque below ~ 10 MHz
  - Actual frequency highly dependent on solar cycle, location, …
- Moon has no permanent atmosphere/ionosphere

LWDA Movie