21 cm and Physics on the "Dark Side" of the Moon

CIPANP 2022

August 31, 2022

Kaja Rotermund

On behalf of the LuSEE-Night Team

Brookhaven National Laboratory

BERKELEY LAB

Space Sciences Laboratory SSL UC Berkeley ssl.berkeley.edu

UNIVERSITY OF MINNESOTA

Outline

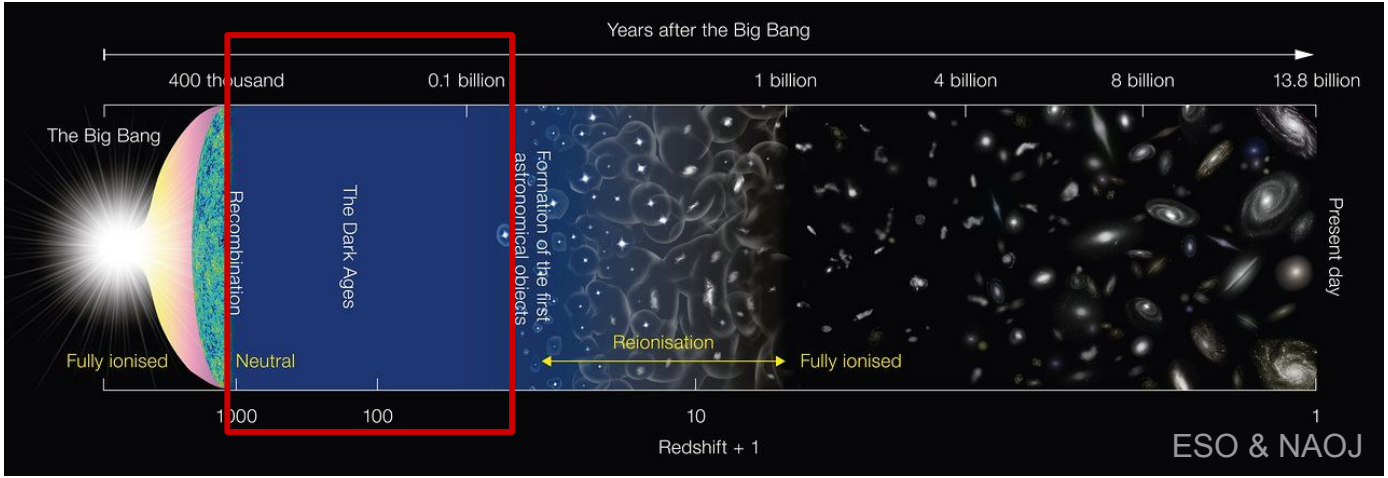
- Science Introduction
  - Dark Ages
  - Global 21-cm Spectrum
  - Lunar Far-Side
- Project Overview
  - LuSEE-Night Instrument

Science

The Dark Ages

- Period between CMB and Cosmic Dawn
- No compact radiation sources → linear physics

One of the least constrained frontiers of modern cosmology!



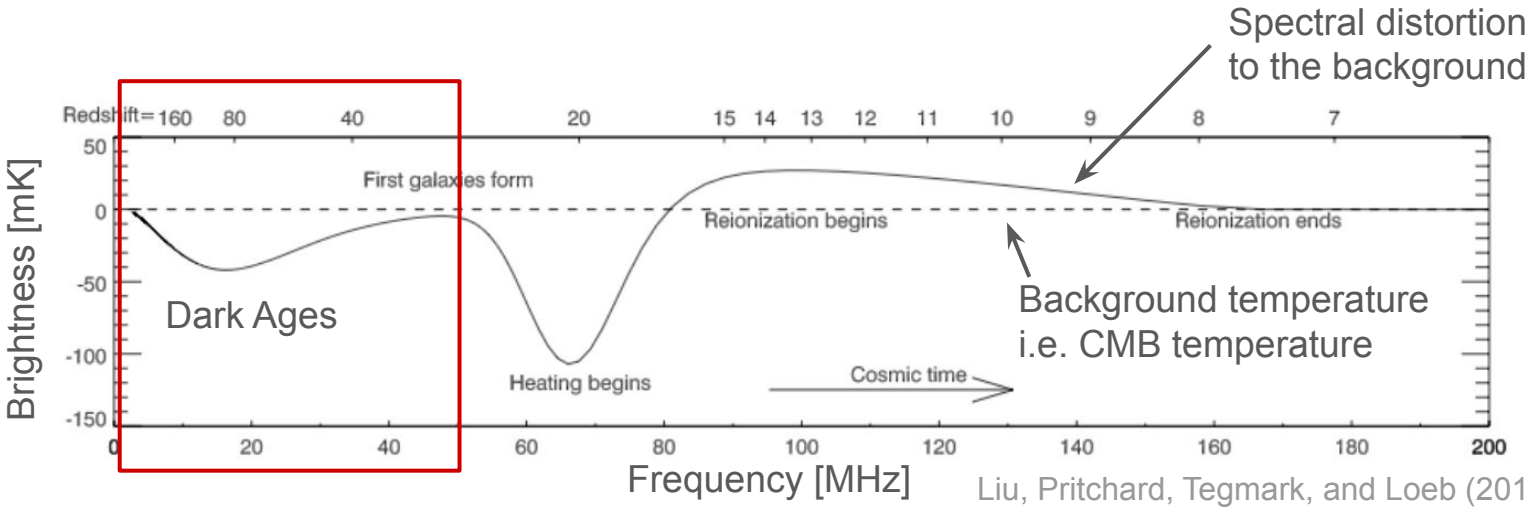
What *can* we observe? ➜ Hydrogen density

Ubiquitous neutral hydrogen

- Spin-flip, hyperfine transition
- Single known method to observe the Dark Ages

The global 21-cm spectrum

- Observe the resulting absorption/emission spectrum against the CMB
- Dark Ages trough: 0.5-50 MHz

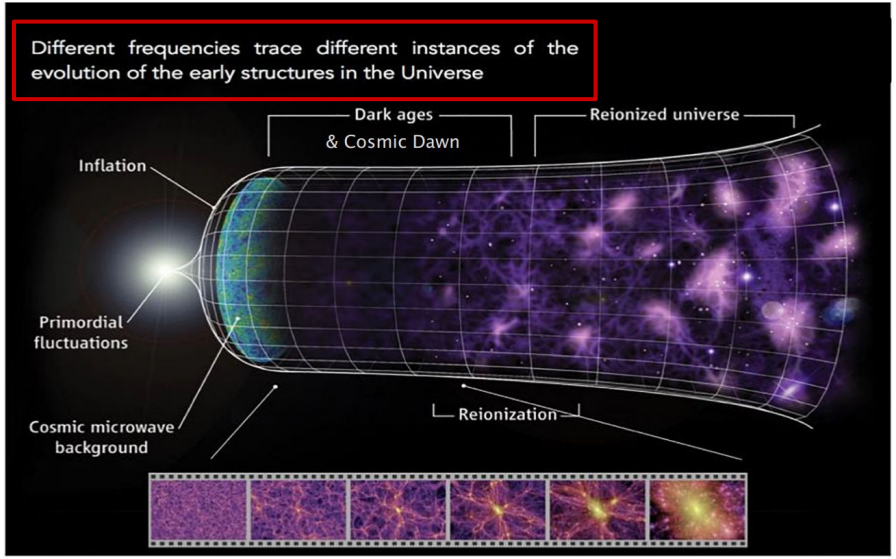


Liu, Pritchard, Tegmark, and Loeb (2013)

Why observe the Dark Ages?

Test our knowledge of fundamental physics & further constrain ΛCDM models

- Precision cosmology
  - Free of astrophysical complexity
  - More constraining than CMB
    - ➢ 3D volume vs 2D shell
- Beyond the standard model
  - Inflationary models
    - ➢ Effect of gravitational waves on large scale structure (Masui & Pen 2010)
  - Neutrinos
    - ➢ Constrain neutrino decay lifetimes (Chianese et al. 2019)
  - Dark matter
    - ➢ Annihilation or decay (Koopmans et al. 2021)



Koopmans et al. (2021)

Any measured deviation → immediate & profound implications on fundamental physics

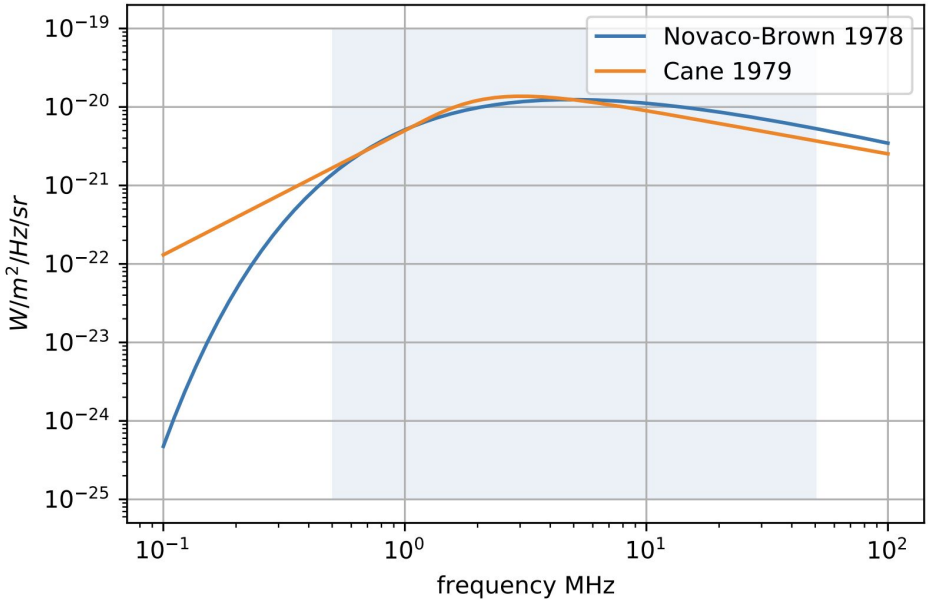
Strong community support & interest

"The panel sees ***21 cm*** and molecular line intensity mapping of the ***Dark Ages*** and reionization era as both ***the discovery area for the next decade*** and as the likely ***future technique for measuring the initial conditions of the universe*** in the decades to follow."

Astronomy & Astrophysics Decadal Survey - 2020s

Challenges of the Dark Ages signal ➜ foregrounds

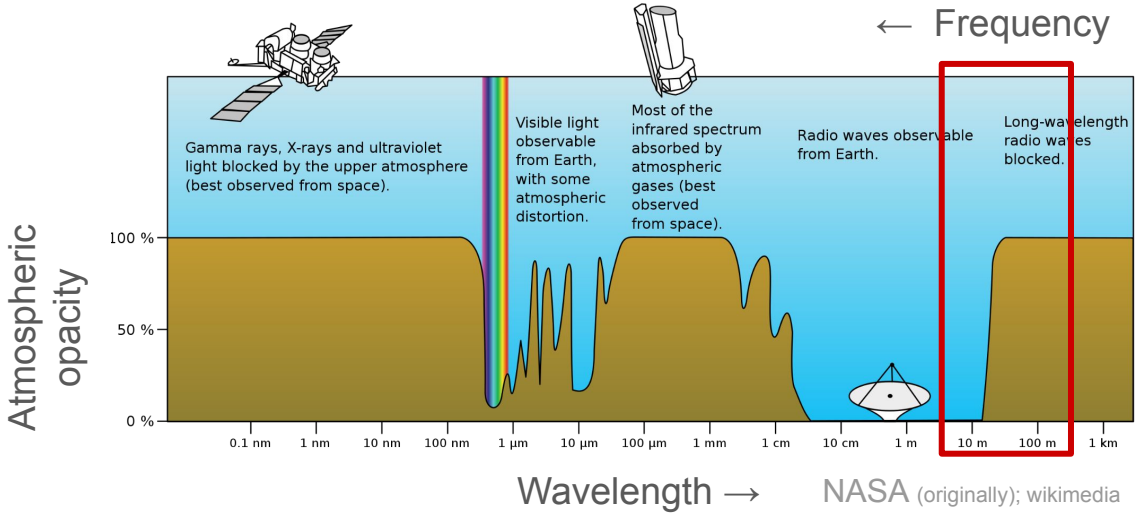
- Bright galactic emission
  - *Foregrounds not well described by power-laws due to free-free absorption*
  - *But…* spectrally smooth → can be removed due to difference in relative strength between foregrounds and 21 cm signal



From *where* can we observe the 21 cm spectrum?

- Earth
  - Ionosphere is opaque at these low frequencies
  - Strong terrestrial RFI

The Dark Ages are impossible to observe from Earth

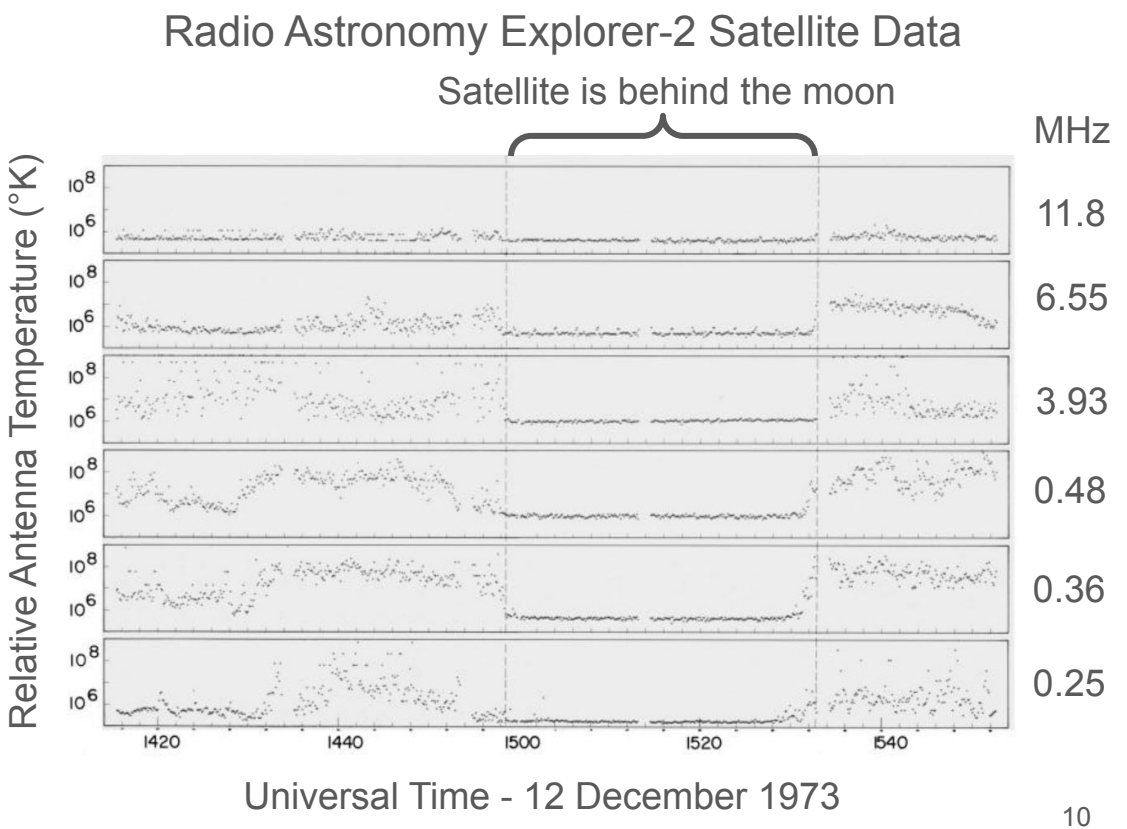


NASA (originally); wikimedia

Ground-based experiments can access:
Epoch of Reionization: 100-200 MHz
Cosmic Dawn trough: 50-100 MHz

The lunar far-side

- No (significant) ionosphere
- Far-side
  - Radio quiet
- Lunar Nights
  - Stable
  - Avoid interference from solar RF emissions

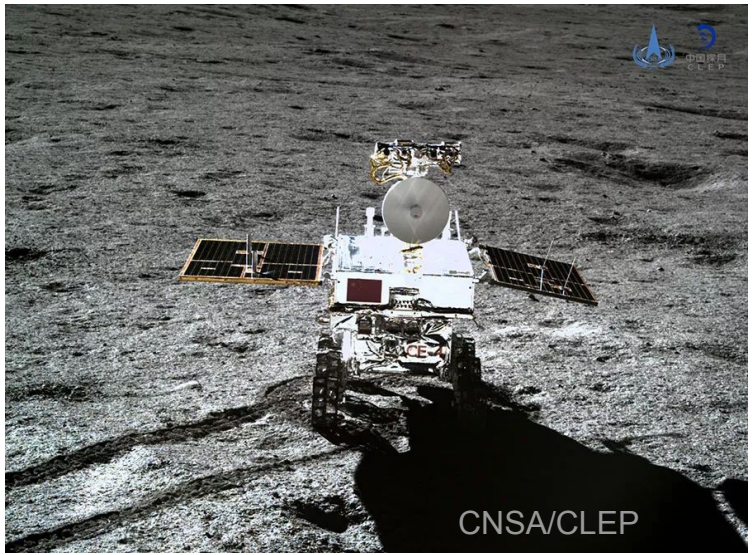


Alexander et al. (1975)

What/who is on the lunar far-side?

China’s Chang’E 4 mission - Jia et al. (2018)

- First mission to the lunar far-side
- Landed January 3, 2019
- Goals
  - Low-frequency radio astronomy
    - ➢ Observed their own emission
  - Study lunar environment



LuSEE-Night

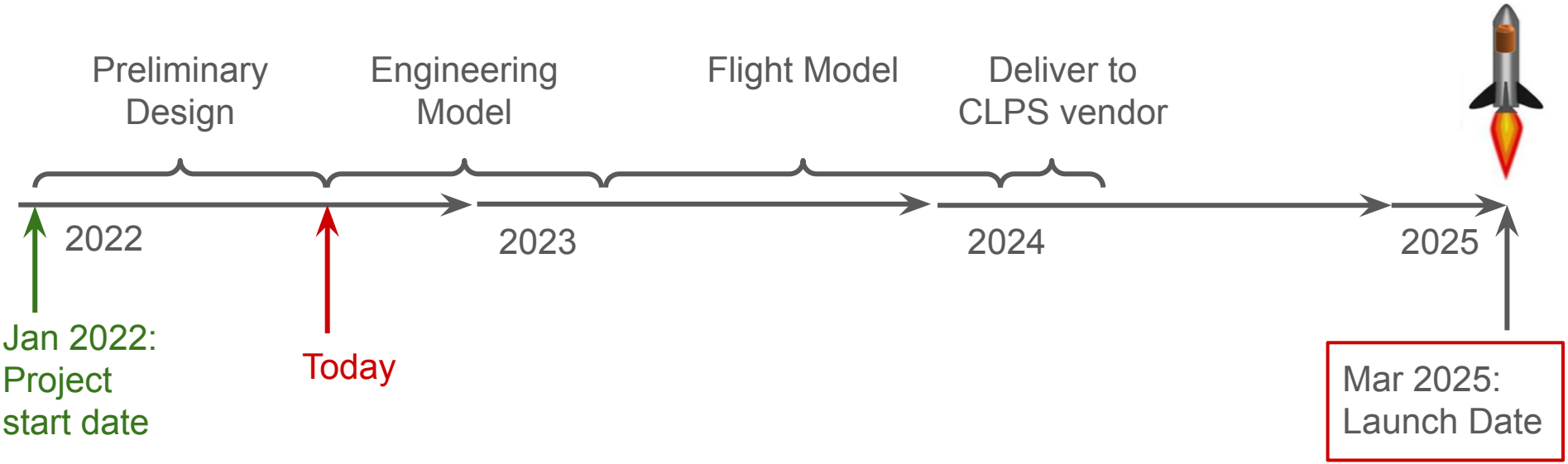
(Lunar Surface Electromagnetic Explorer at Night)

Origins of LuSEE-Night

- Proposed to NASA by UC Berkeley's Space Science Lab (SSL)

- Up-Scope opportunity with DOE augmentation identified
  - ➢ Lunar night survival
  - ➢ Improved spectrometer
  - ■ BNL selected as lead lab for DOE augmentation

Timeline


Preliminary Design
Engineering Model
Flight Model
Deliver to CLPS vendor
2022
2023
2024
2025
Jan 2022: Project start date
Today
Mar 2025: Launch Date

The LuSEE-Night Hardware Team

- BNL
  - Spectrometer
  - Integrated electronics assembly
  - Power distribution
  - Telemetry
- LBNL
  - Antenna
- SSL
  - Payload module
  - Thermal control
  - System integration
- University of Minnesota
  - System engineering
  - Low EMI power supply

Brookhaven National Laboratory

BERKELEY LAB

Space Sciences Laboratory SSL UC Berkeley ssl.berkeley.edu

UNIVERSITY OF MINNESOTA

How do we get there?

Commercial Lunar Payload Services

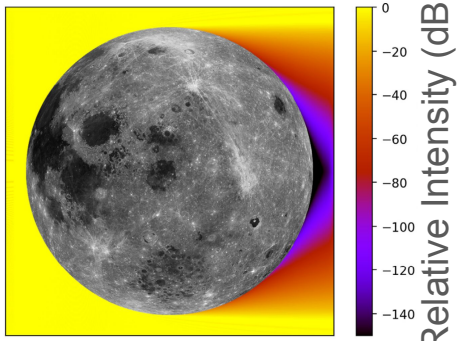
A NASA initiative - rapid delivery of payloads to the lunar surface by American companies

https://www.nasa.gov/content/commercial-lunar-payload-services

Potential landing site requirements:

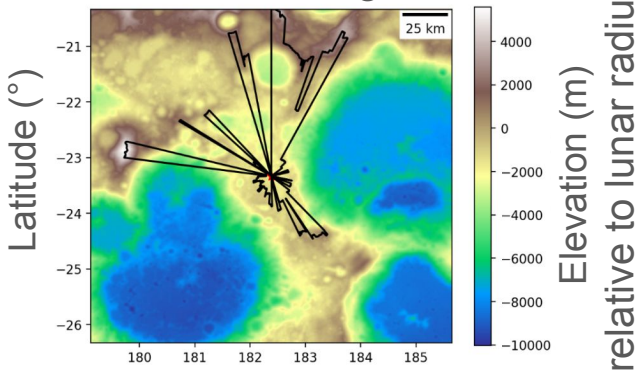
- low RFI
- flat site
- low & far hills
- no magnetic anomalies

RF attenuation at 30 kHz



Bassett et al. (2020)

Black curve traces topographical features defining horizon

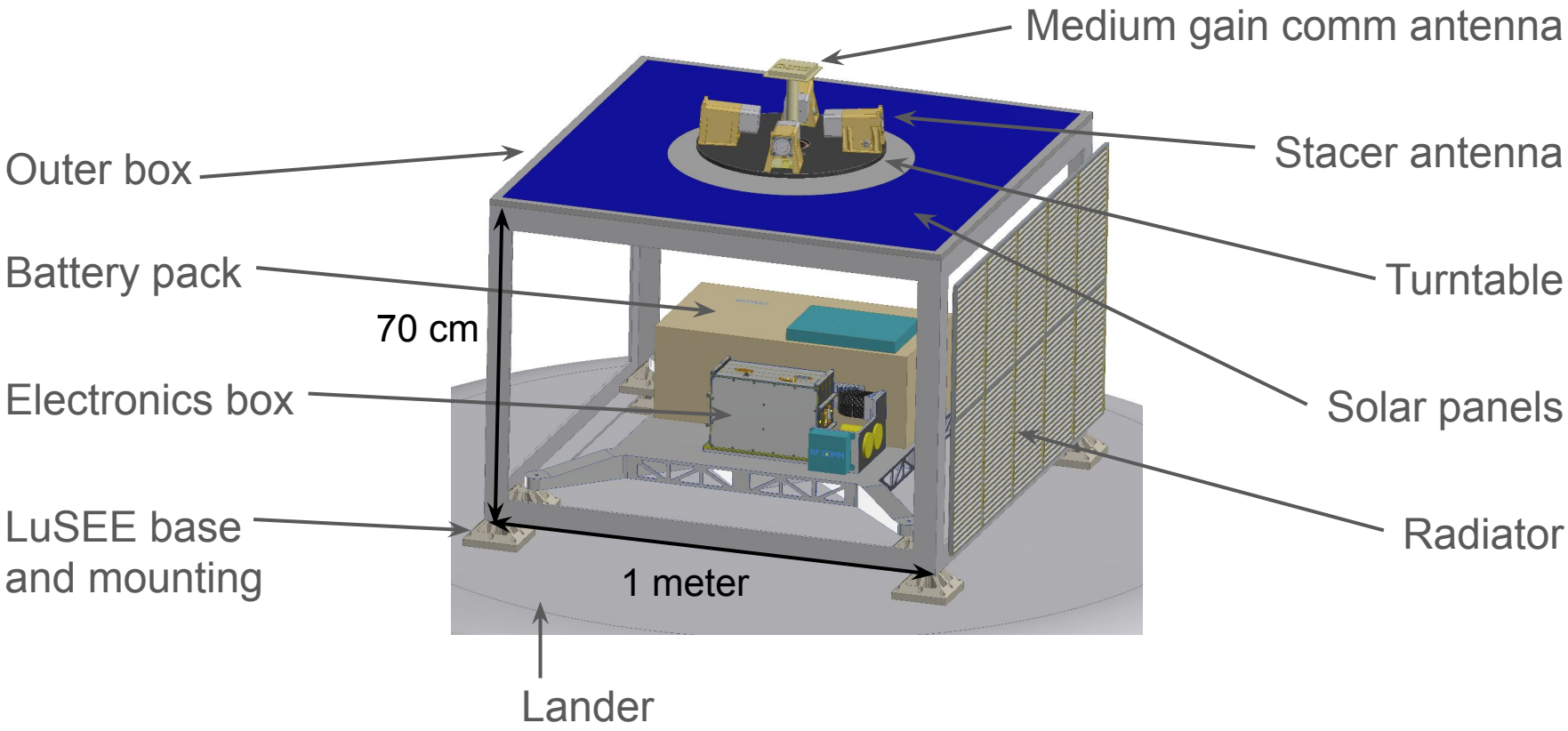


Lunar QuickMap

LuSEE-Night goals

- Establish the lunar surface as a viable site for low-frequency radio astronomy
- Perform the most sensitive observations of the radio sky at 0.5-50 MHz
- Characterize foregrounds at low frequencies
- Place the most stringent constraints on the Dark Ages trough to date

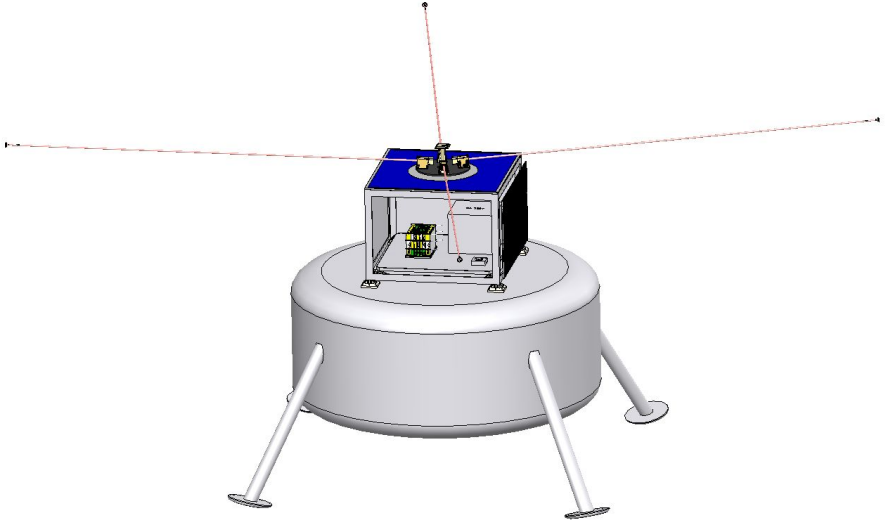
LuSEE-Night payload



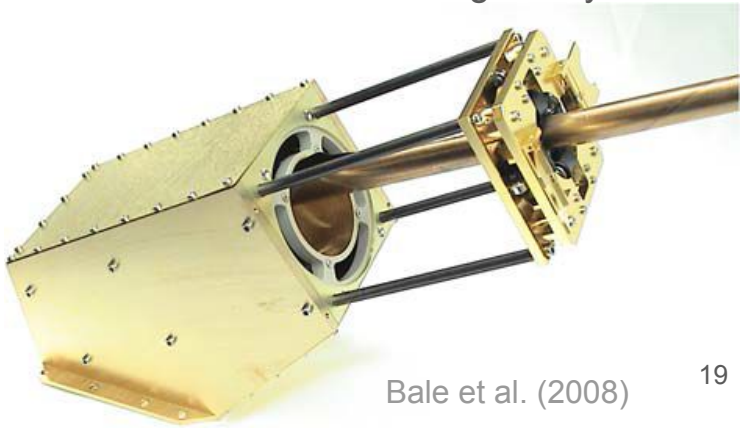
Antennas

- Design requirements:
  - High TRL → previously flown in several space missions
  - Light, compact
  - Smooth chromatic response

4x 3 meter monopole antennas



Stacer antenna module designed by SSL



Bale et al. (2008)

Spectrometer

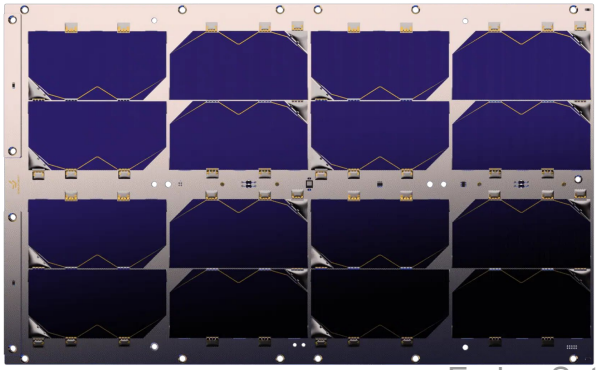
JFET amplifier parameter	LuSEE-Night
JFET	**LSK489A**
Low noise	**e_n = 1.8nV/√Hz**
Low input capacitance	**Ciss = 4pF**

- Enhanced RF Spectrometer flown with FIELDS (Parker Solar Probe)
- JFET amplifier (analog)
- FPGA board (digital)

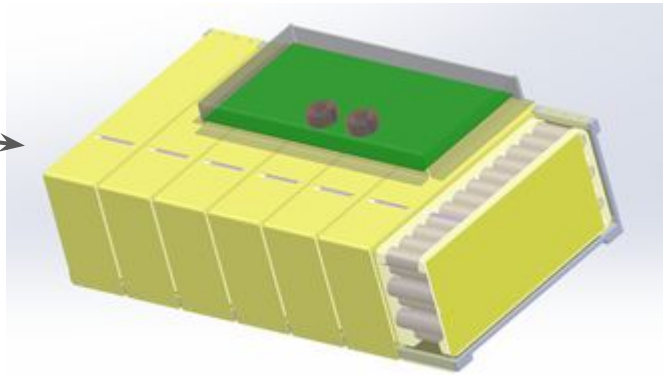
Spectrometer parameter	LuSEE-Night
Frequency range	**0.5 – 50.0 MHz**
Digitizer channels	**4**
Sampling clock	**125 MSPS**
Duty factor	**50-90%**
FPGA	**RTG4, 65nm**
Correlation products	**6**
Transient capture	**Yes**

Power delivery

- Recharge during day
- Power instrument throughout lunar night
  - ~ 336 hr
- Photovoltaic:
  - InGaP/GaAs/Ge triple-junction cells
  - 96 W nominal output
- High-capacity battery:
  - 28 V
  - 8225 W-h capacity
  - 42 kg



EnduroSat



Mechanical & thermal design

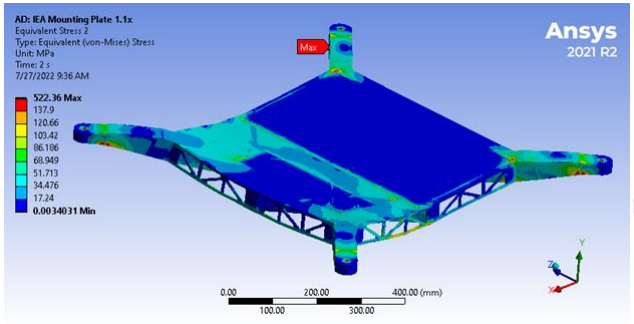
Mechanical:

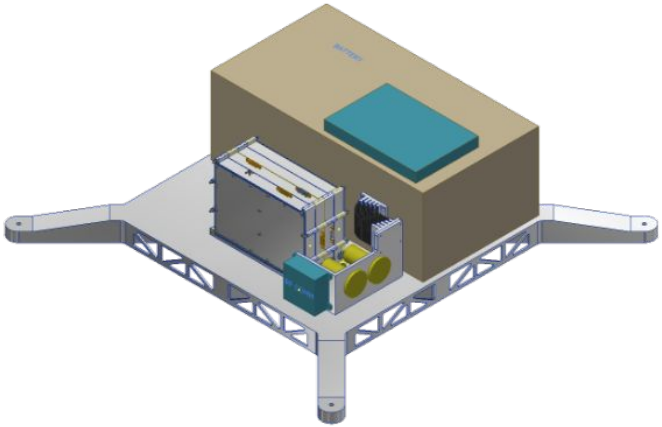
- Survive launch & landing
  - Machined Al plate with honeycomb structure

Thermal:

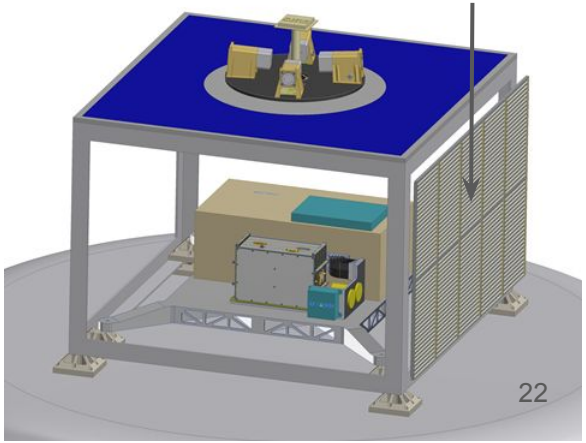
- Survive extreme temperature fluctuations
  - Day ~ 400 K → heat rejection: heat switches & radiator
  - Night ~ 100 K → heat retention: MLI

< 2 mm deflection under 30 g acceleration

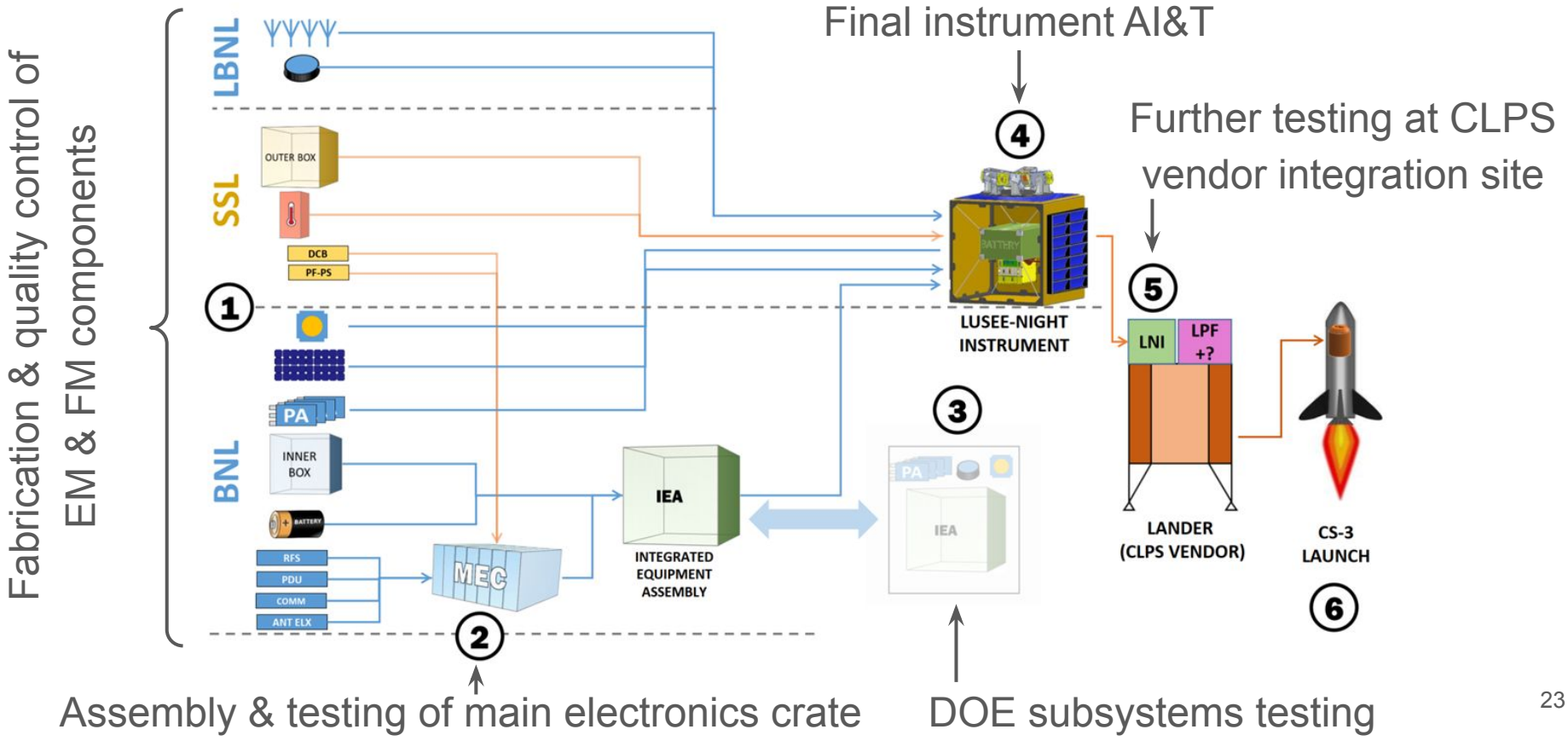




Radiator

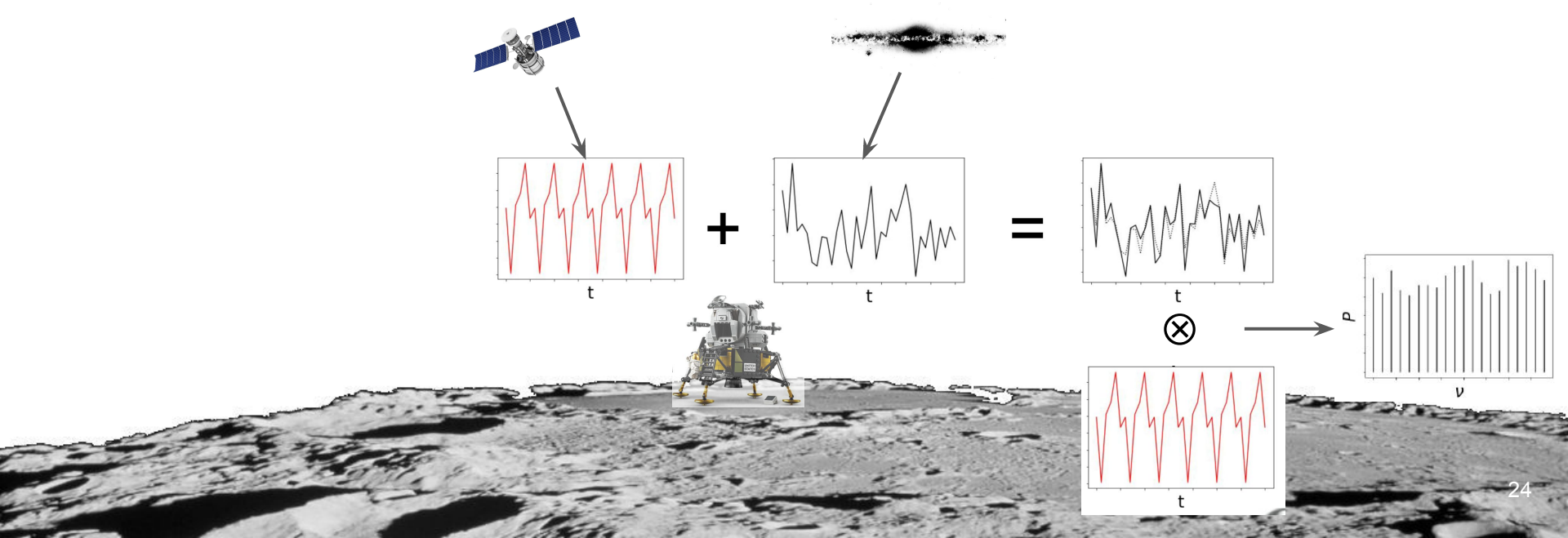


Assembly, integration & test



Calibration

- Digital calibration source (in orbit around the moon)
  - Emits a known coded broadband signal
  - Enables precision understanding of the beam pattern and its chromaticity

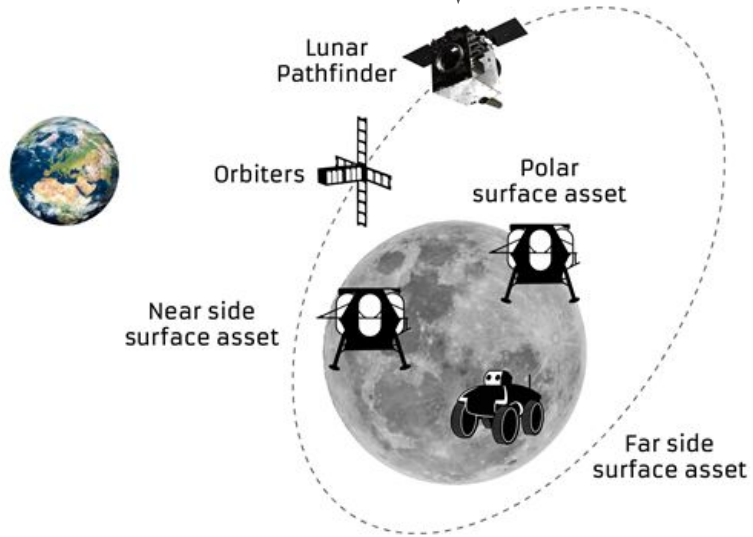


Communication - data management

- Data sent to science operations center via periodic contact with an orbiting relay satellite
  - Communications link: S-band radio transmitter
- Deliver ~6 GB of science and telemetry data every lunar cycle
- Up to 24 cycles depending on equipment survival

Item	Size (GB)
Main auto- and cross-power spectra	1 – 2
Additional power spectra	1 – 4
Housekeeping	0.5
Snapshot raw streams	1 – 2
TOTAL	3.5 – 8.5

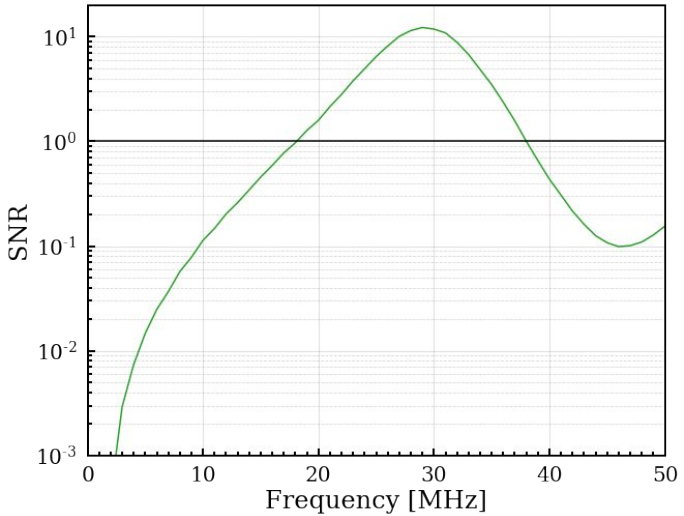
European Space Agency's Lunar Pathfinder Satellite, will launch on the same rocket as LuSEE-Night



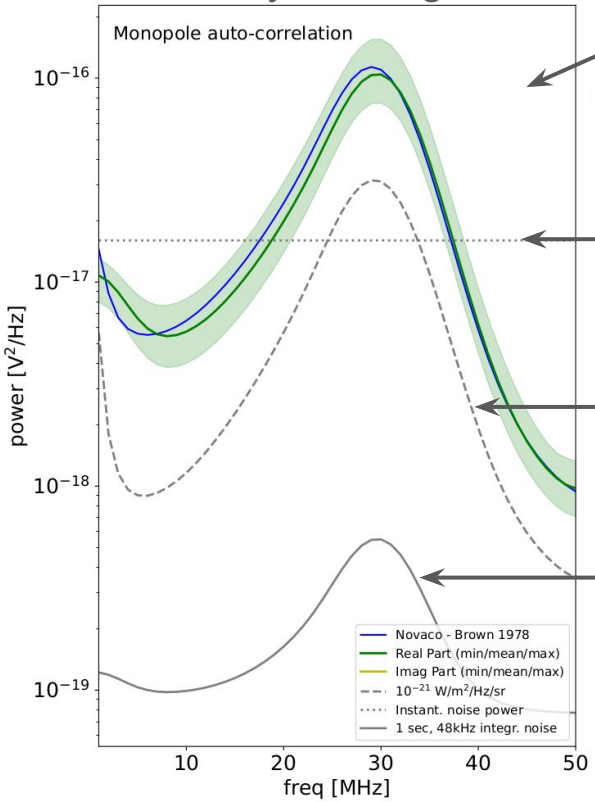
Performance Forecast

- Key performance criteria:
  - Sensitive to galactic signal at 10^{-21} W/m^2/Hz/sr

Dark Ages trough SNR
1 lunar night



Sensitivity to foregrounds



High sensitivity across the band

Instantaneous noise

Power from uniform sky load

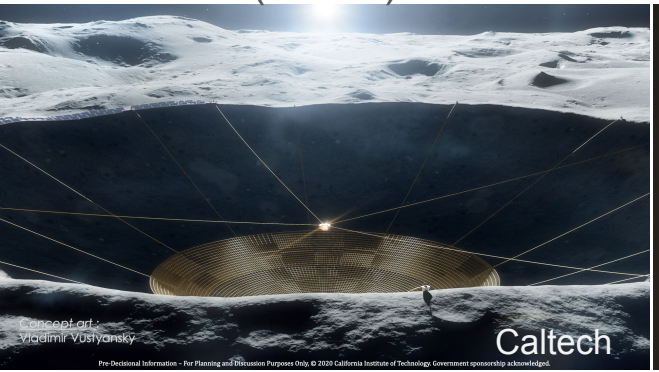
Noise level per bin (1 sec integration)

LuSEE-Night is a pathfinder…

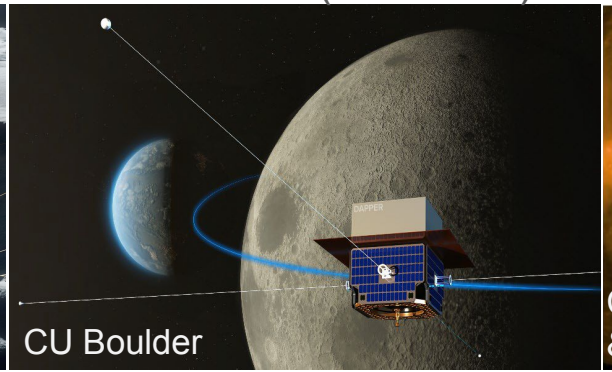
… both in location, foregrounds and science goals!

Other lunar pathfinder experiments targeting the Dark Ages:

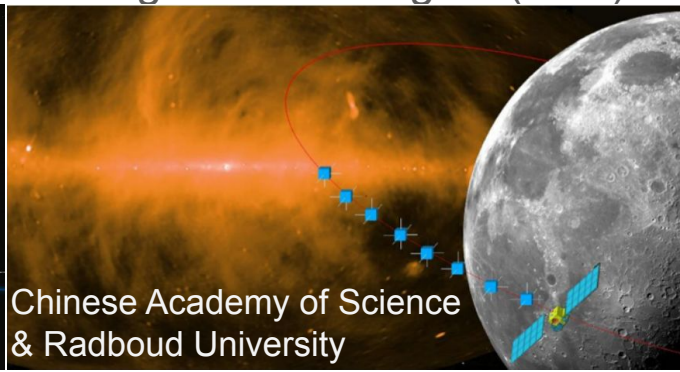
Lunar Crater Radio Telescope (LCRT)



Dark Ages Polarimetry PathfindER (DAPPER)



Discovering the Sky at the Longest Wavelengths (DSL)



LuSEE-Night will perform sensitive observations of the radio sky at 0.5-50 MHz from the radio-quiet Lunar far-side.

Thank You.


Brookhaven
National Laboratory


BERKELEY LAB

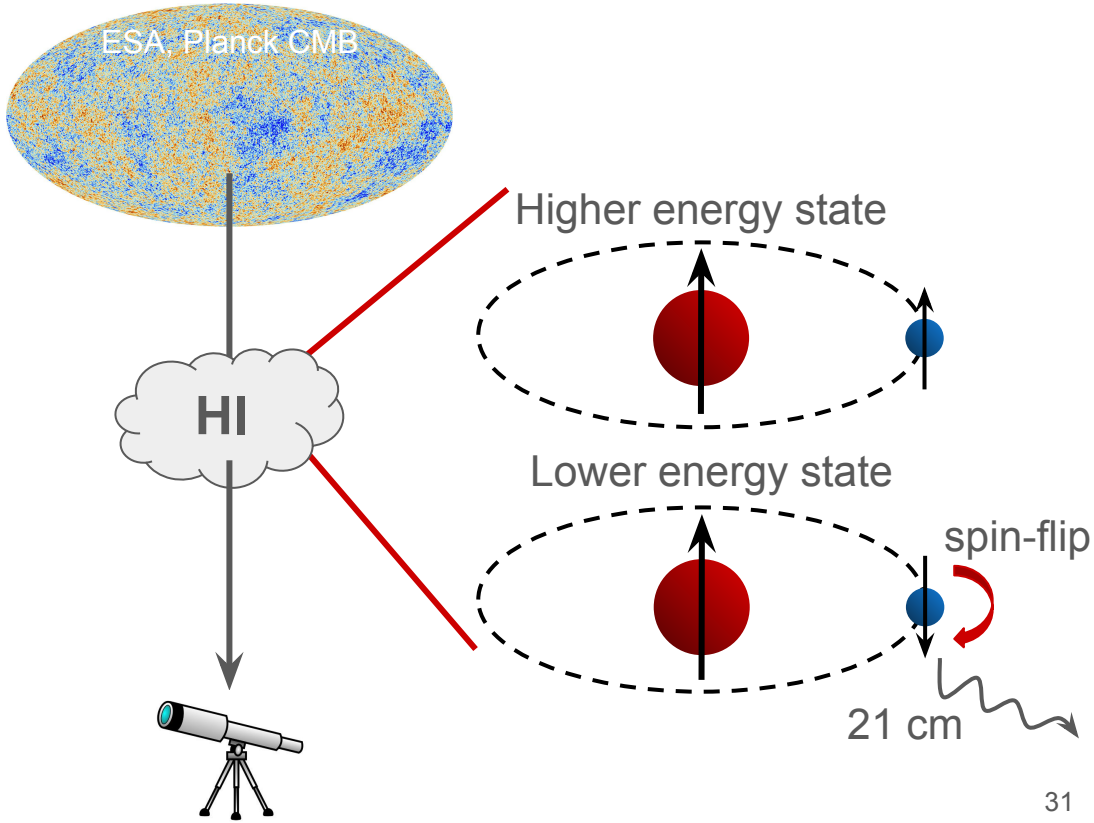

Space Sciences Laboratory
SSL
UC Berkeley
ssl.berkeley.edu


UNIVERSITY OF MINNESOTA

Backup Slides

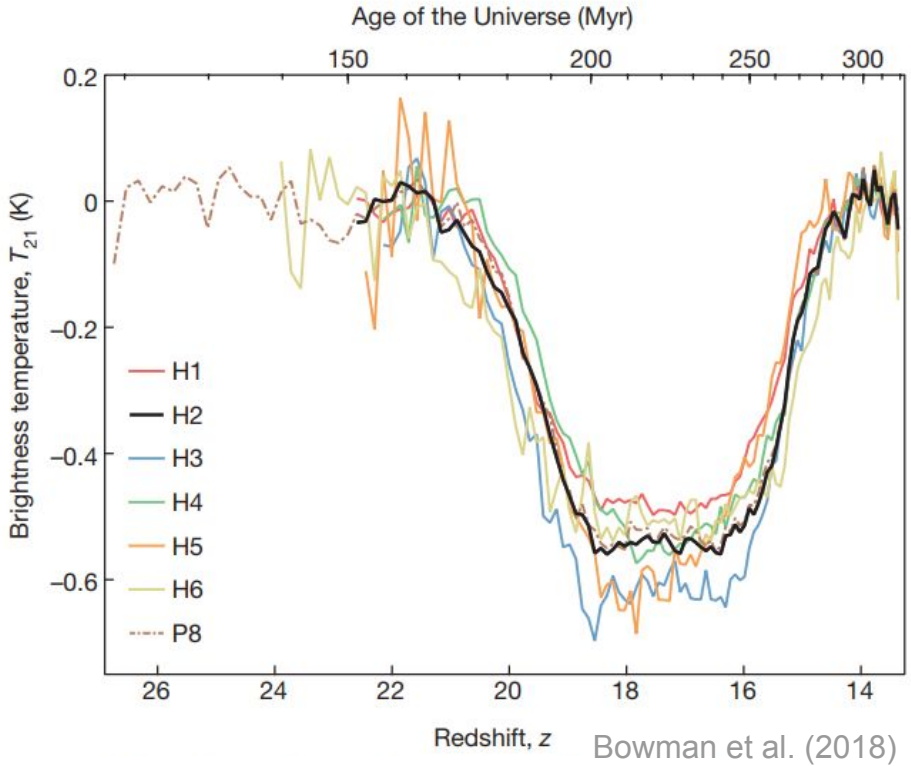
What *can* we observe? ➜ Hydrogen emission

- Ubiquitous neutral hydrogen
- Redshifted 21-cm emission:
  - Single known method to observe the Dark Ages



EDGES

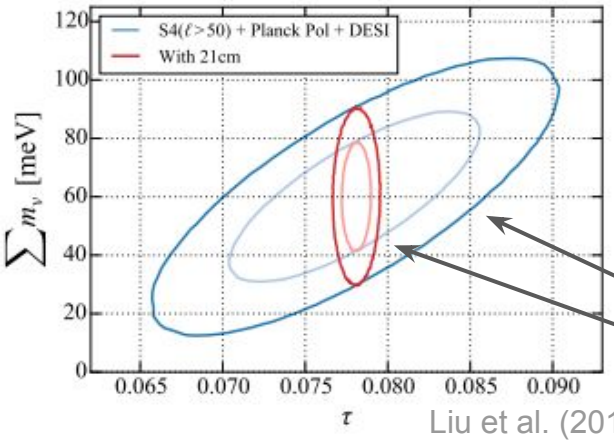
- First reported detection of the Cosmic Dawn trough
  - Centered at 78 MHz (z = 17)
  - Amplitude: 0.5 K
- Requires independent confirmation
  - Suggests exotic interactions
    - ➢ i.e. baryon - dark matter



Bowman et al. (2018)

Benefits of 21 cm

- Neutral hydrogen provides 3D maps
  - Significantly more precise constraints on cosmological parameters
  - Neutrino mass & spatial curvature density parameter: 3x improvement (Mao et al. 2008)

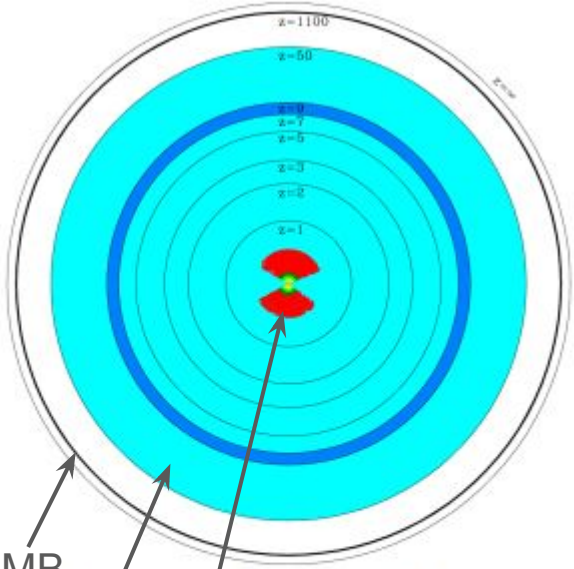


Liu et al. (2015)

21 cm breaks degeneracy of optical depth (τ) and neutrino mass (m_ν)

CMB-stage 4 experiments

21 cm



CMB

21 cm

Sloan Digital Sky Survey

Mao et al. (2008)

Abstract

The "Dark Ages" refers to the cosmic era between the last scattering of the cosmic microwave background and “Cosmic Dawn,” the time when the first stars and galaxies formed. Only cold, non-luminous hydrogen gas existed during the Dark Ages, which emits at 21 cm (f = 1420 MHz). Through the expansion of the universe, this signal has been redshifted to low radio frequencies that are inaccessible from earth due to distortions of our ionosphere and significant terrestrial radio-frequency interference. This era is therefore largely unexplored and remains one of the least constrained frontiers of modern cosmology. LuSEE-Night is a project that aims to make sensitive measurements across two decades in frequency space from the radio-quiet far side of the moon. In doing so, LuSEE-Night will determine the feasibility of conducting radio-frequency astronomy from the lunar surface and acts as a pathfinder for larger missions in the future.