LuSEE-Night

A Pathfinder Radio Telescope on the Far Side of the Moon

Anže Slosar, Brookhaven National Laboratory

BNL, Physics Colloquium
28 July 2026

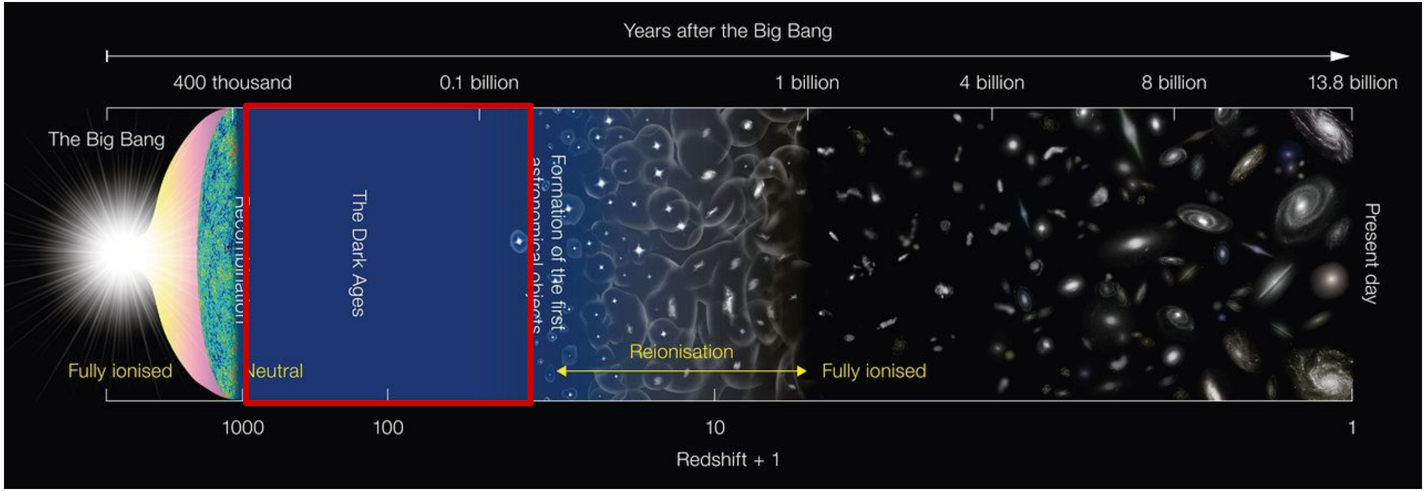
TL;DR

- LuSEE-Night is a pathfinder telescope on the far side of the Moon:
  - ontological advantage over other experiments
    - it is happening!
  - Launch expected in winter 2026, landing early 2027
- Moon is hard!! Harder than space and harder than Mars
- Frequency range <30 MHz largely unexplored:
  - 21cm Dark Ages is a Platonic goal
  - Other exciting science possibilities abound

The Dark Ages

- Period between CMB and Cosmic Dawn
- No compact radiation sources → linear physics
- No compact radiation sources → no optical radiation to observe

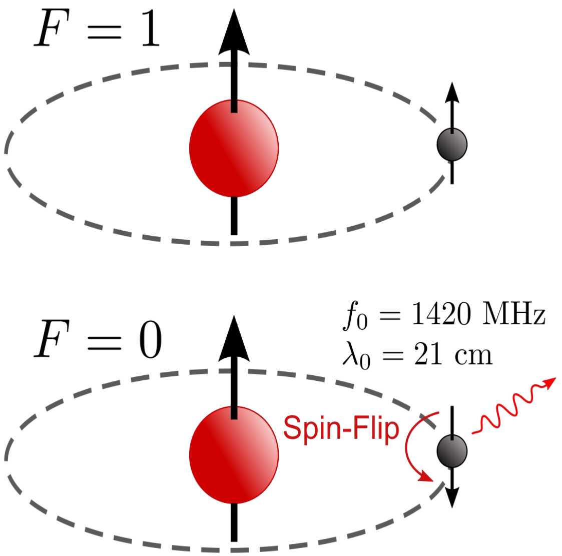
One of the least constrained frontiers of modern cosmology!



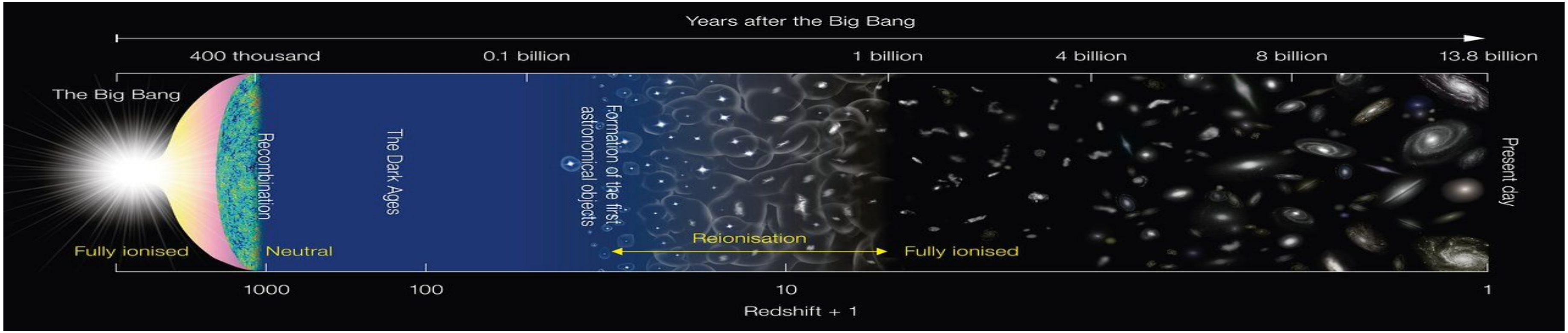
ESO & NAOJ

21cm emission

- Hyperfine transition in neutral hydrogen at ν=1420MHz, λ=21.1cm;
- This is the **only** transition around -- if you see a line at 710MHz, it is a z=1 galaxy;
- (not true in optical)
- Universe is mostly hydrogen (75%)
- Hydrogen is in various states and 21cm emission dominated by different mechanism across the cosmic ages
- NB: you need atomic hydrogen: neither ionized nor molecular hydrogen work



21cm shines differently at different epochs



Dark Ages	Epoch of Reionization	Low redshift
$20 \lesssim z \lesssim 150$	$6 \lesssim z \lesssim 20$	$z \lesssim 6$

Dark Ages

$20 \lesssim z \lesssim 150$

- Pristine primordial density field
- We see 21cm in emission / absorption against CMB light from the global density field

Epoch of Reionization

$6 \lesssim z \lesssim 20$

- First stars and galaxies are reionizing universe
- Large bubbles of ionized gas among neutral medium
- Signal driven by astrophysics
- Non-DOE science

Low redshift

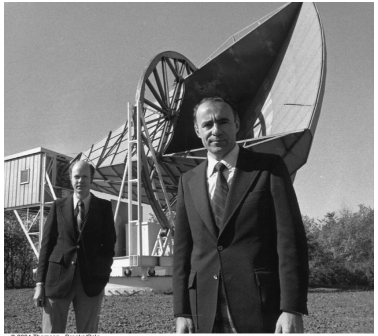
$z \lesssim 6$

- Universe is reionized
- pockets of neutral hydrogen in galaxies
- Very similar science to standard galaxy surveys
- We don't aim to go after individual galaxies

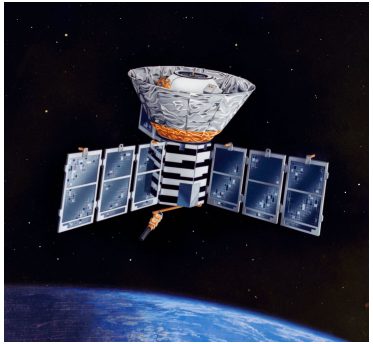
You eat the elephant in small pieces

CMB

- Monopole discovered 1965 by Penzias and Wilson (Nobel Prize in 1978)



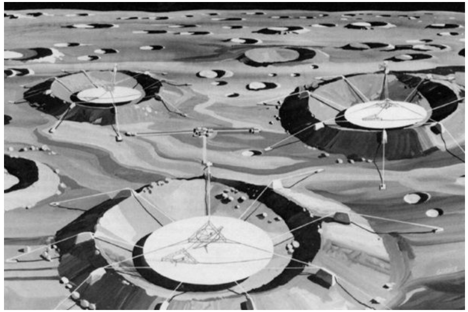
- Fluctuations discovered 1990 by COBE satellite (Smoot's Nobel Prize in 2006)



Dark Ages

- Monopole detected 2030s (?)

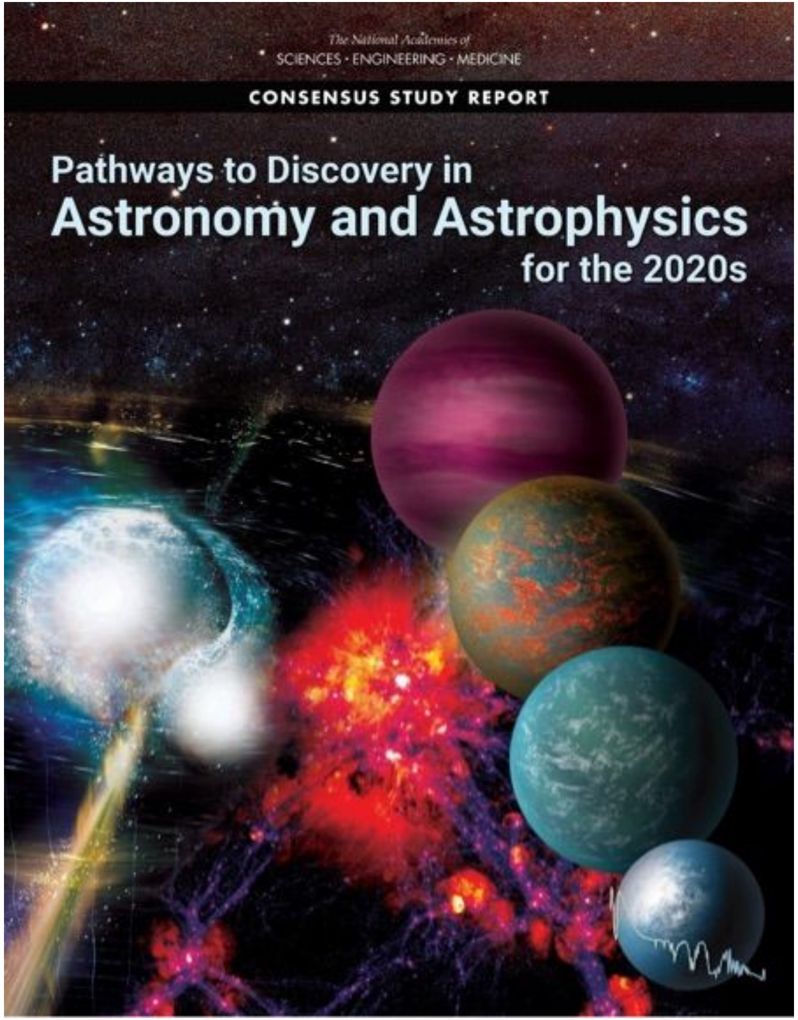
- Fluctuations detected 2060(?)



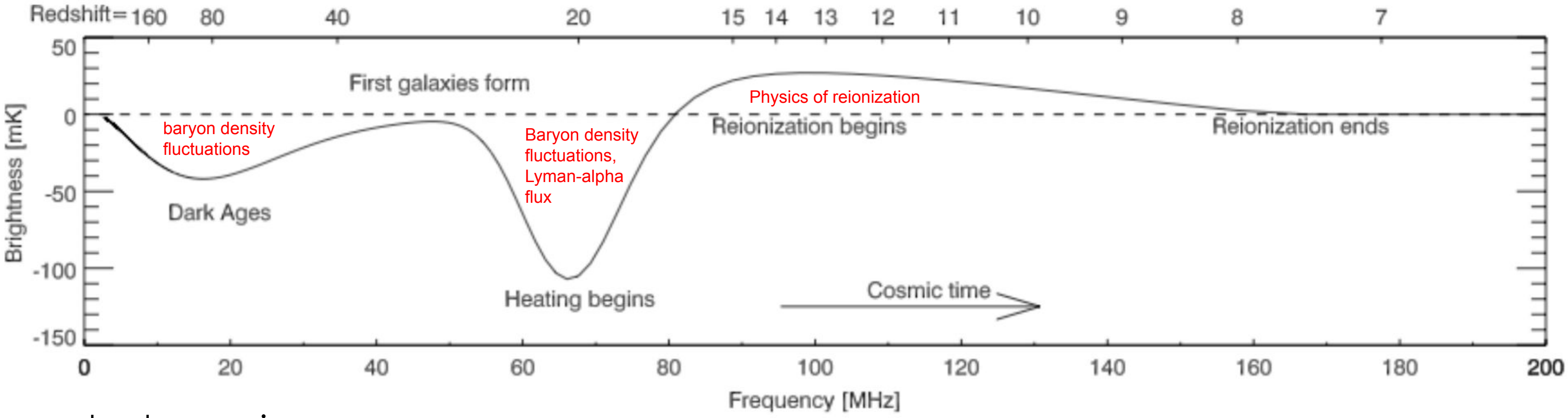
Decadal Survey on Astronomy & Astrophysics,
Panel on Cosmology p.258

DISCOVERY AREA: THE DARK AGES AS A COSMOLOGICAL PROBE

"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.



Physics of the 21cm monopole



We see hydrogen in contrast with CMB. There can be net absorption or net emission:

$$\delta T_b = \frac{T_S - T_R}{1+z}(1 - e^{-\tau_\nu}) \approx \frac{T_S - T_R}{1+z}\tau$$

Three processes matter:

- absorption / emission from CMB
- collisions with other particles
- Wouthuysen-Field effect (resonant scattering of Ly-alpha photons)

- **$200 \lesssim z \lesssim 1100$**: The residual free electron fraction left after recombination allows Compton scattering to maintain thermal coupling of the gas to the CMB, setting $T_K = T_\gamma$. The high gas density leads to effective collisional coupling so that $T_S = T_\gamma$ and we expect $\bar{T}_b = 0$ and no detectable 21 cm signal.
- **$40 \lesssim z \lesssim 200$**: In this regime, the gas cools adiabatically so that $T_K \propto (1+z)^2$ leading to $T_K < T_\gamma$ and collisional coupling sets $T_S < T_\gamma$, leading to $\bar{T}_b < 0$ and an early absorption signal. At this time, T_b fluctuations are sourced by density fluctuations, potentially allowing the initial conditions to be probed [32, 22].
- **$z_\star \lesssim z \lesssim 40$**: As the expansion continues, decreasing the gas density, collisional coupling becomes ineffective and radiative coupling to the CMB sets $T_S = T_\gamma$, and there is no detectable 21 cm signal.

(Pritchard and Loeb review, 2011)

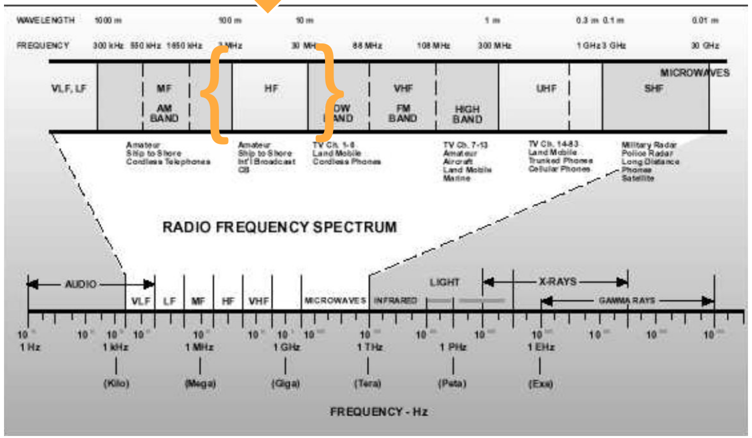
Dark Ages Monopole: A cosmic calorimeter

- The size of the dark ages through is sensitive to any non-standard energy injection or sink in the early universe.
- Measuring it would be confirmation of our understanding of thermodynamics in the post-CMB era
- Deviations would imply something from a large menu of options:
  - dark matter-baryon scattering
  - millicharged dark matter
  - dark matter annihilation
  - axions
  - neutrino decay
  - charge sequestration
  - quark nuggets
  - dark photons
  - interacting early dark energy
  - …

What do we need to measure this?

Objective:

- observe the sky at low radio frequencies (0.5 – 50MHz) where the Dark Ages signal lives



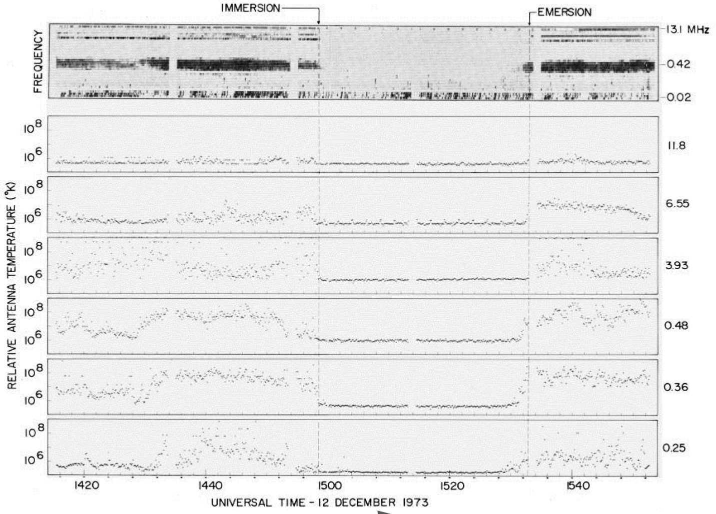
Impossible from Earth:

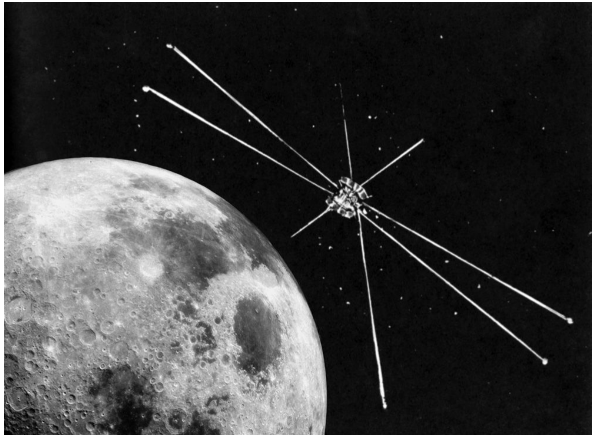
- RF contamination from anthropogenic and atmospheric sources
- Ionosphere absorbs, emits, and refracts at these frequencies

Solution:

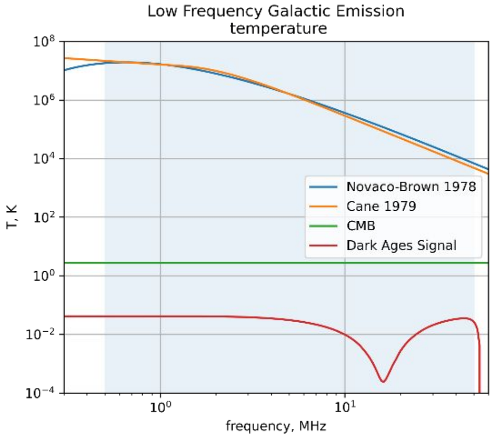
- Telescope on the Moon's far side is protected from terrestrial RFI
- The Moon has no atmosphere → no ionospheric distortions
- During the lunar night, solar RFI is also blocked
- Alternatives with their own advantages and disadvantages:
  - Lunar Orbit
  - Outer solar system

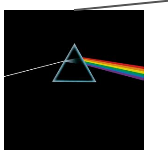
What do we know about low-frequency sky





Radio-Astronomy-Explorer-2 was the largest spacecraft ever built with four 230m antennas





The Dark Side of the Moon by Pink Floyd released in March 1973

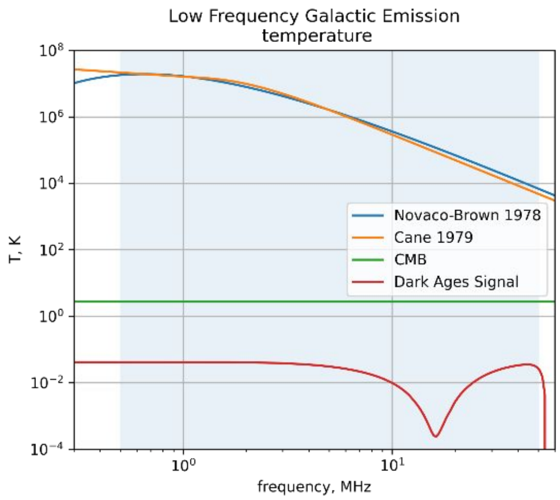
- We have empirical evidence that the far side of the moon is radio-quiet
- Caveat: in orbit, not on the surface

- Last real data on the low-frequency sky from the late 1970s
- Still state-of-the-art dataset to be superseeded

- Dark Ages signal is dominated by orders of magnitude brighter synchrotron emission from Galaxy

Even without Dark Ages: low frequency sky unknown at O(1)

- It is very easy to hide new physics at very low frequencies
- For all we know, CMB could be 1000s of K at low
  frequency
- O(1) lines could exist pointing at new DM physics or interactions
- Making maps, even crude maps at frequencies below 20 MHz would push the field forward



Lots of interesting science

- Hope for the unexpected:
- Blind search for radio lines
- Very bright CMB
- Polarization rotation
- An unexpected news class of transients
- … science book coming out soon!

$\textit{In Situ}$ Measurements of Dark Photon Dark Matter Using Parker Solar Probe: Going beyond the Radio Window

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Dark photon dark matter (DPDM) emerges as a compelling candidate for ultralight bosonic dark matter, detectable through resonant conversion into photons within a plasma environment. This Letter employs

New Physics in the Rayleigh-Jeans Tail of the CMB

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[4]*Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, 1050 Vienna, Austria*
[5]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[6]*INFN, sezione di Trieste, SISSA, via Bonomea 265, 34136 Trieste, Italy*
(Dated: September 14, 2018)

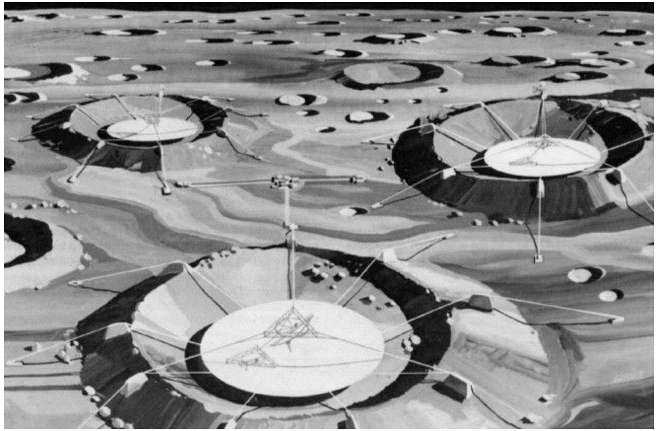
We show that despite stringent constraints on the shape of the main part of the CMB spectrum, there is considerable room for its modification within its Rayleigh-Jeans (RJ) end, $\omega \ll T_{\rm CMB}$. We construct explicit New Physics models that give an order one (or larger) increase of photon count in the RJ tail, which can be tested by existing and upcoming experiments aiming to detect the cosmological 21 cm emission/absorption signal. This class of models stipulates the decay of unstable

Searches for signatures of ultralight axion dark matter in polarimetry data of the European Pulsar Timing Array

N. K. Porayko[1,2,*] P. Usynina,[3,†] J. Terol-Calvo[4,5,6,‡] J. Martin Camalich[4,5] G. M. Shaifullah[1,7,8] A. Castillo[9] D. Blas[10,11] L. Guillemot[12,13] M. Peel[14] C. Tiburzi[8] K. Postnov[3,15] M. Kramer[2,16] J. Antoniadis[17,2] S. Babak[18] A.-S. Bak Nielsen[2,19] E. Barausse[20,21] C. G. Bassa[22] C. Blanchard[12,13] M. Bonetti[1,7,23] E. Bortolas[1,7,24] P. R. Brook[25] M. Burgay[8] R. N. Caballero[26] A. Chalumeau[22] D. J. Champion[2]

How to build a telescope on the Moon?

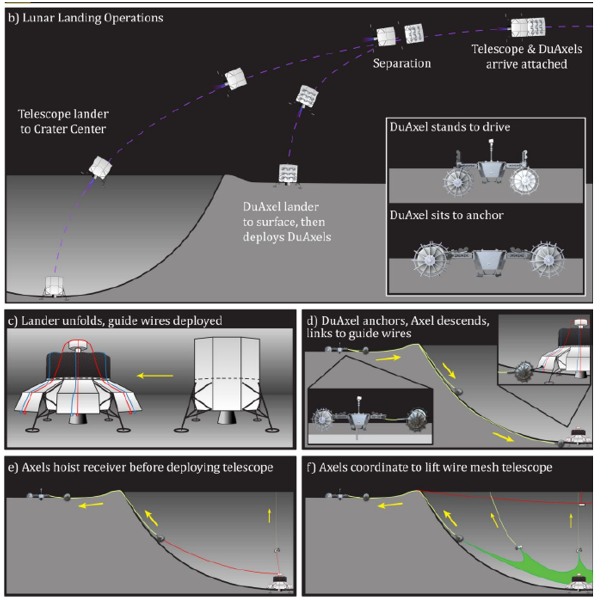
- People were daydreaming about putting a telescope of the far side of the Moon since 1950s
- Richard Vondrak working at Apollo Science Operations Center proposed using lunar craters to build radio telescopes like the Arecibo Observatory in Puerto Rico.

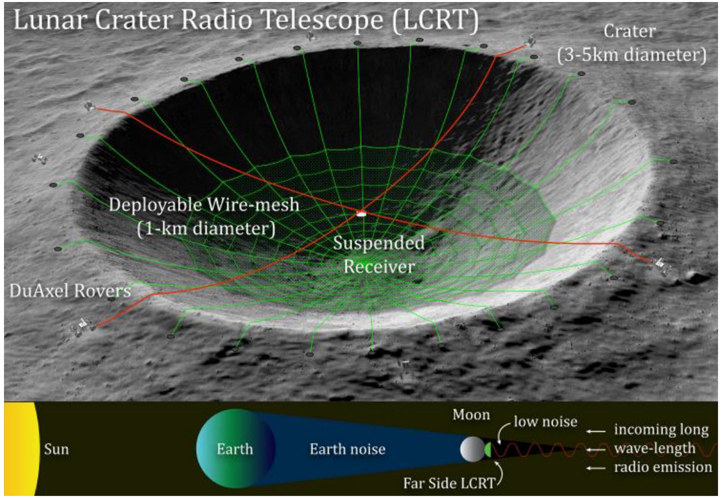


1950s concept from Apollo times: Arecibos in Lunar Crater

Arecibo (now decommissioned)

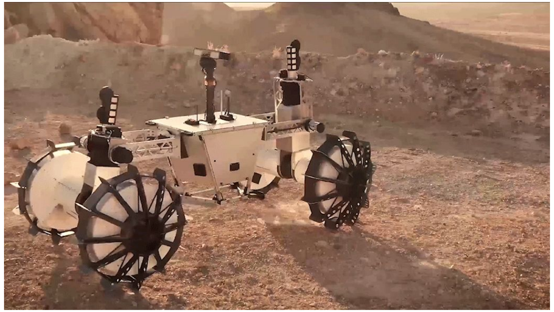
Lunar Crater Radio Telescope



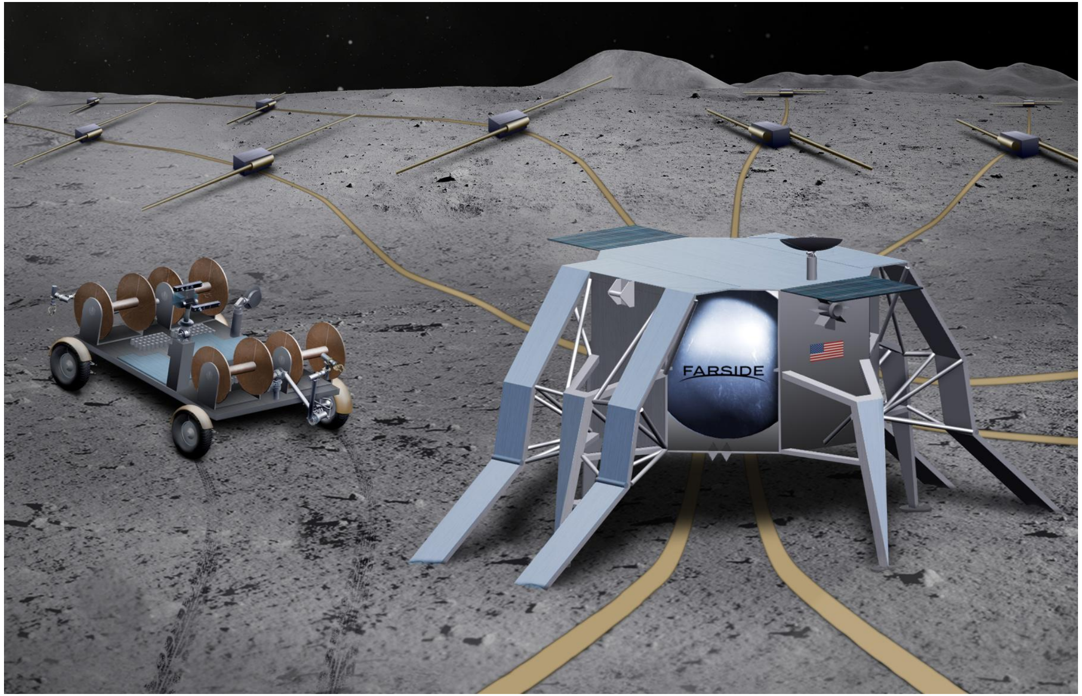


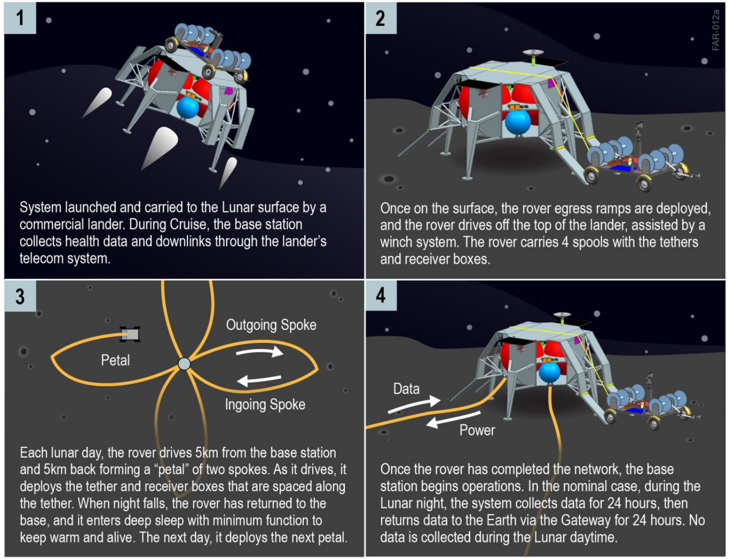
LCRT: modern incarnation of the crater concept
PI: Saptarshi Bandyopadhyay

DuAxels
actually exist



FARSIDE:



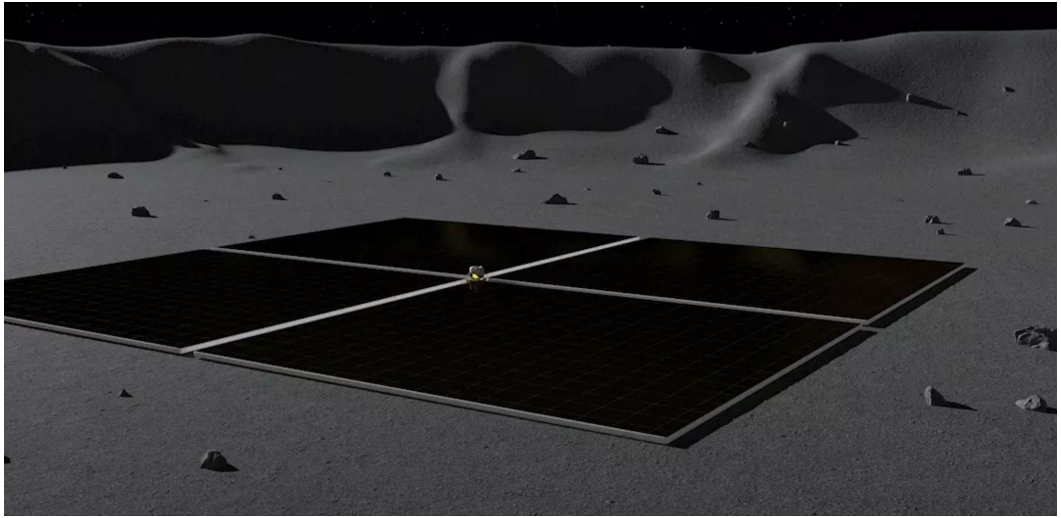


Lands and installs a 128-node interferometric array of dipole antennas

PI Jack Burns

ALO: Astronomical Lunar Observatory

- Inflatable 32x32 array
- 1-80 MHz, total cargo ~1500kg
- launch ~2027-2029
- PI: Marc Klein Wolt
- ESA funded conceptual design level, designed by ASTRON in Netherlands
- See Koopmans' talk



Motivated by the hierarchy problem….

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PAPER

A very high energy hadron collider on the Moon

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Keywords: high-energy physics, future colliders, beyond the standard model, high-temperature superconductors, lunar science, space travel, megastructures

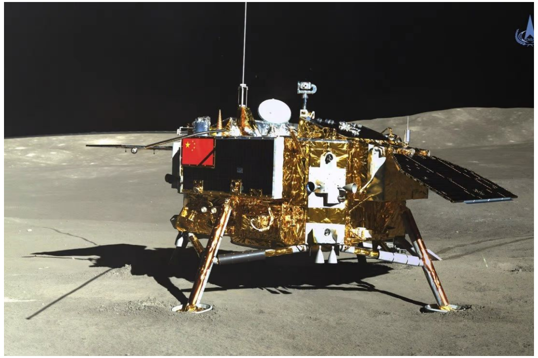
Abstract

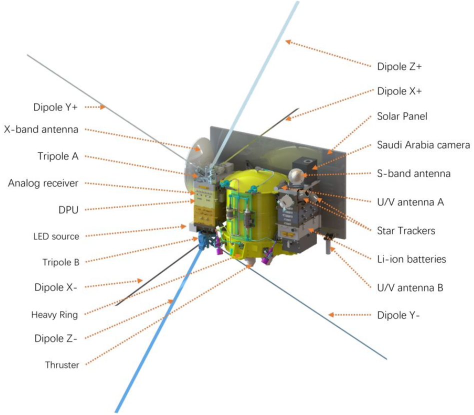
The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A circular collider on the Moon (CCM) of ~11 000 km in circumference could reach a proton–proton center-of-mass collision energy of 14 PeV—a thousand times higher than the Large Hadron Collider at CERN—optimistically assuming a dipole magnetic field of 20 T. Several aspects of such a project are presented, including siting, construction, availability of necessary materials on the Moon, and powering, as well as a discussion of future studies and further information needed to determine the more concrete feasibility of each. Machine parameters and vacuum requirements are explored, and an injection scheme is delineated. Other unknowns are set down. Due to the strong interest from multiple organizations in establishing a permanent Moon presence, a CCM could be the (next-to-) next-to-next-generation discovery machine for high-energy particle physics and a natural successor to next-generation machines, such as the proposed future circular collider at CERN or a super proton–proton collider in China, and other future machines, such as a collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone toward a Planck-scale collider sited in our Solar System.

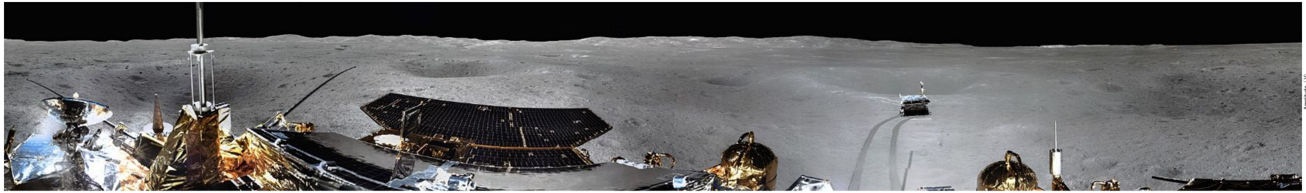

Bayt.com Blog:
Back to Reality: How to Ease into Work After a Relaxing Vacation

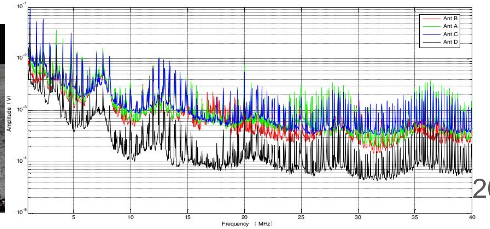
Chang’e-4

- Chinese Lander to the Far Side of the Moon
- Achieved first soft landing on the far side of the Moon, on 3 January 2019
- Carried Low. Frequency Radio Spectrometer (LFRS) on lander
- Carried NCLE (Netherlands-China Low-Frequency Explorer) on relay satellite
- Both instruments believed to be dominated by switching noise
- carried extra antenna to detect that, but no cigar





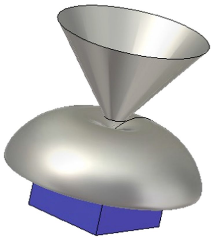




Do you want to be on the Moon or in orbit?

Advantages of orbit:

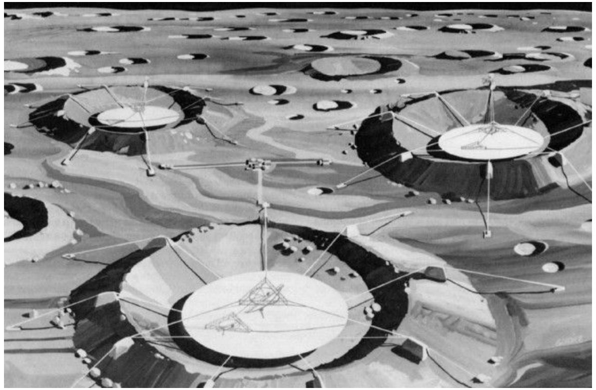
- system to simulate is compact and considerably smaller than wavelength
  - The entire system can be made geometrically simple and symmetric
- power management is easier: can re-charge every few hours
- orbit is cheaper than landing
- easy to implement rotation modulation (e.g. through tumble)



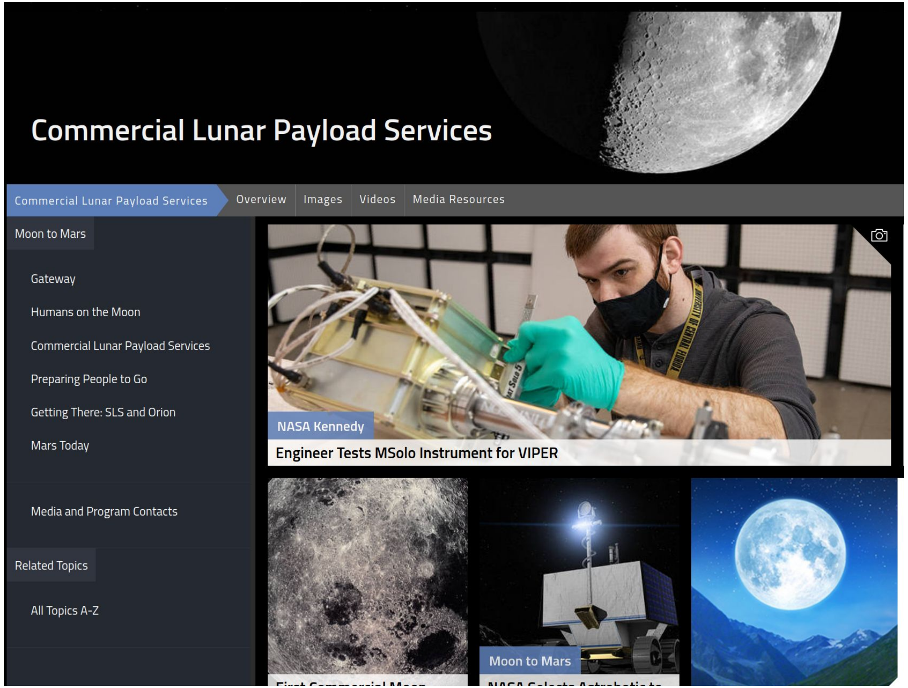
PRATUSH concept

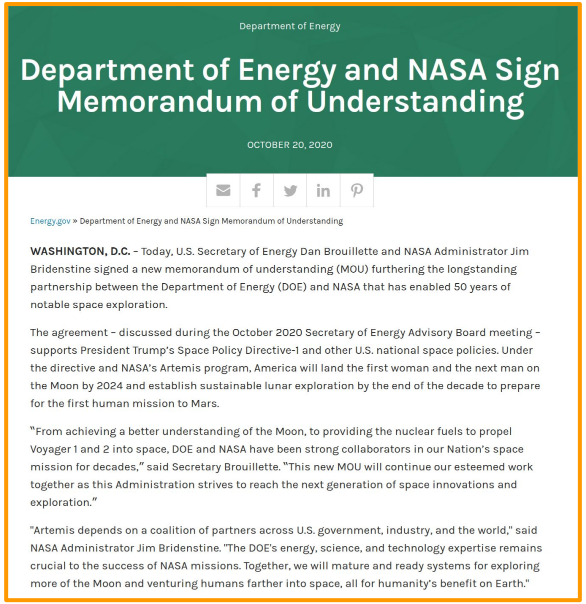
Advantages of lunar surface:

- Long, stable nights
- Stabler baselines for interferometers
- Potentially quieter environment with less dense plasma



Meanwhile, in the US…




Department of Energy

Department of Energy and NASA Sign Memorandum of Understanding

OCTOBER 20, 2020

Energy.gov » Department of Energy and NASA Sign Memorandum of Understanding

WASHINGTON, D.C. – Today, U.S. Secretary of Energy Dan Brouillette and NASA Administrator Jim Bridenstine signed a new memorandum of understanding (MOU) furthering the longstanding partnership between the Department of Energy (DOE) and NASA that has enabled 50 years of notable space exploration.

The agreement – discussed during the October 2020 Secretary of Energy Advisory Board meeting – supports President Trump's Space Policy Directive-1 and other U.S. national space policies. Under the directive and NASA's Artemis program, America will land the first woman and the next man on the Moon by 2024 and establish sustainable lunar exploration by the end of the decade to prepare for the first human mission to Mars.

"From achieving a better understanding of the Moon, to providing the nuclear fuels to propel Voyager 1 and 2 into space, DOE and NASA have been strong collaborators in our Nation's space mission for decades," said Secretary Brouillette. "This new MOU will continue our esteemed work together as this Administration strives to reach the next generation of space innovations and exploration."

"Artemis depends on a coalition of partners across U.S. government, industry, and the world," said NASA Administrator Jim Bridenstine. "The DOE's energy, science, and technology expertise remains crucial to the success of NASA missions. Together, we will mature and ready systems for exploring more of the Moon and venturing humans farther into space, all for humanity's benefit on Earth."

- Increased desire for NASA/DOE cooperation as part of Artemis program
- CLPS looking for "oven-ready" payloads

CLPS - Commercial Lunar Payload Services

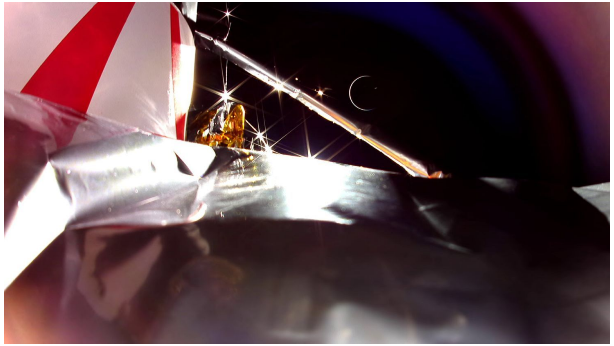
- advent of SpaceX taught NASA that a lot of money can be saved with commercial providers
- a similar program is developed to support Artemis program:
- Now at ~11 eligible vendors that bid on contracts
  - Number of vendors is expected to settle around ~a few.
- awarding 1-4 missions every year
- actively looking for payloads through PRISM (Payloads and Research Investigations on the Surface of the Moon) calls and otherwise
- they view payloads as essentially an exercise in how to run the contracting process

Landers selected in the first round: Peregrine (Astrobotic Technology), Nova-C (Intuitive Machines), Z-01 (OrbitBeyond)

What happened to first CLPS launches.

First CLPS launch:

- January 2024
- Astrobotic, Peregrine
- Launched on an untested ULA rocker
- Rocked performed flawlessly, but mission was doomed almost immediately after separation due to a stuck valve



Second CLPS launch:

- February 2024
- Intuitive Machines, Odysseus,
- Managed to land… sideways
- Carries a radio-instrument called ROLSES
- Many things went wrong with this mission, alm from the get-go
  - none of them was totally catastrophic
  - the company learned an enormous lot

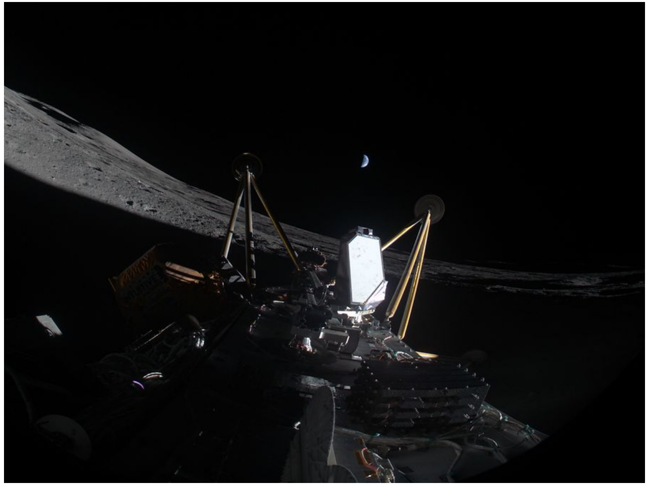
What happened to first CLPS launches.

Third CLPS launch:

- 2nd March 2025
- Firefly Blue Ghost 1
- Landed flawlessly
- Executed operations for entire lunar day

Fourth CLPS launch:

- 6 March 2025
- Intuitive Machines 2, Athena
- Managed to land… sideways… again.



NASA-DOE LuSEE partnership

- UC Berkeley's Space Sciences laboratory (SSL) was chosen to provide a payload for a 2024 CLPS mission.
- Original LuSEE (Lunar Surface Electromagnetics Experiment) targeted plasma science, but incorporated a 20MHz RF spectrometer:
  - concept heavily relied on reusing existing spare parts from Parker Solar Probe
- A synergy with DOE's 21cm cosmology program was realized, and the mission was extended to include a dedicated, multi-night instrument dedicated to Dark Ages science
- Original concept split into 2+1 parts:
  - LuSEE-Lite - focus on day time solar science on CP-12
  - LuSEE-Night - focus on night-time radio science on CS-3
  - Far field calibration "service provision" on CS-4

Parker Solar Probe

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Overarching Science Goals

LuSEE-Night is a pathfinder for the Dark Ages Science from the far-side of the Moon:

Goal 1: ***Establish the Lunar surface as a viable observatory for low-frequency radio astronomy;***

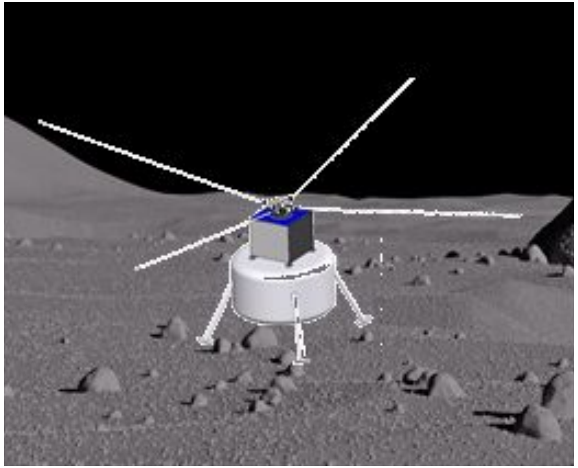
Goal 2: ***Perform the most sensitive observations of the radio sky at 1-50MHz with 20% absolute calibration;***

Goal 3: ***Quantify the systematic effects affecting global spectrum measurement accuracy, and investigate methods to mitigate them;***

Goal 4: ***Constrain the presence of a non-smooth monopole component at the 10^{-3} level compared to foregrounds.***

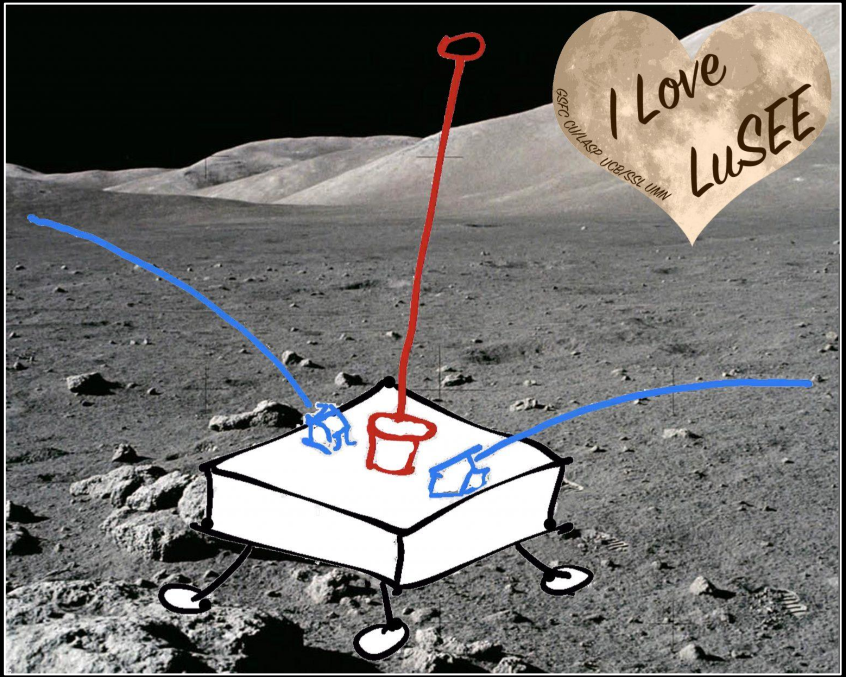
LuSEE-Night instrument

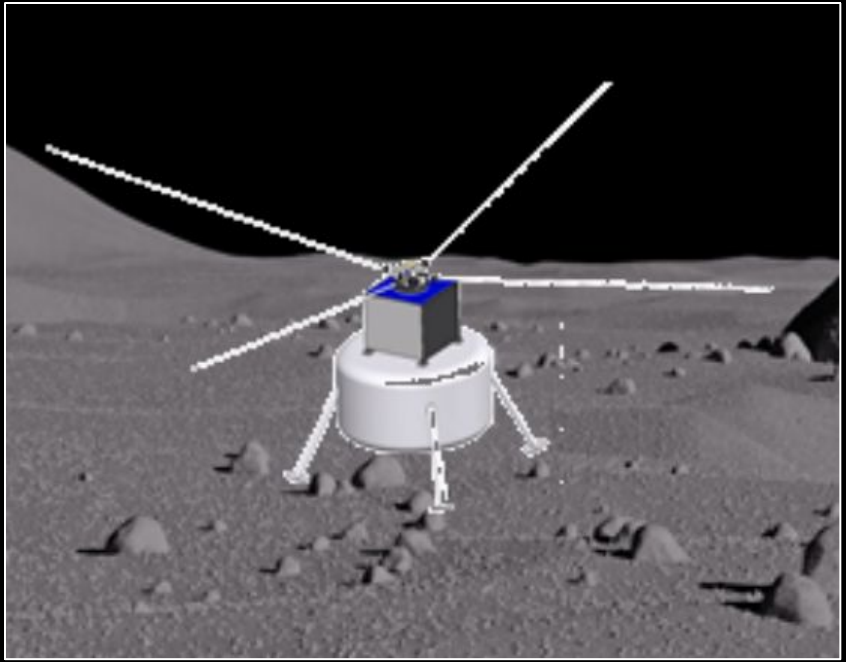
- Instrument design largely driven by the project timeline
- We need to optimize within the limits of:
  - max heritage technology
  - realistic improvements given budget
  - budget includes $, power, time-to-develop
- Basic design includes:
  - 4 STACER antennas
  - ability to actuate in azimuth
  - independently amplified
  - all possible cross-correlations measured and integrated with full bandwidth spectrometer
  - 4 real auto-correlations
  - 6 complex cross-correlation quantities, including two pseudo-dipoles

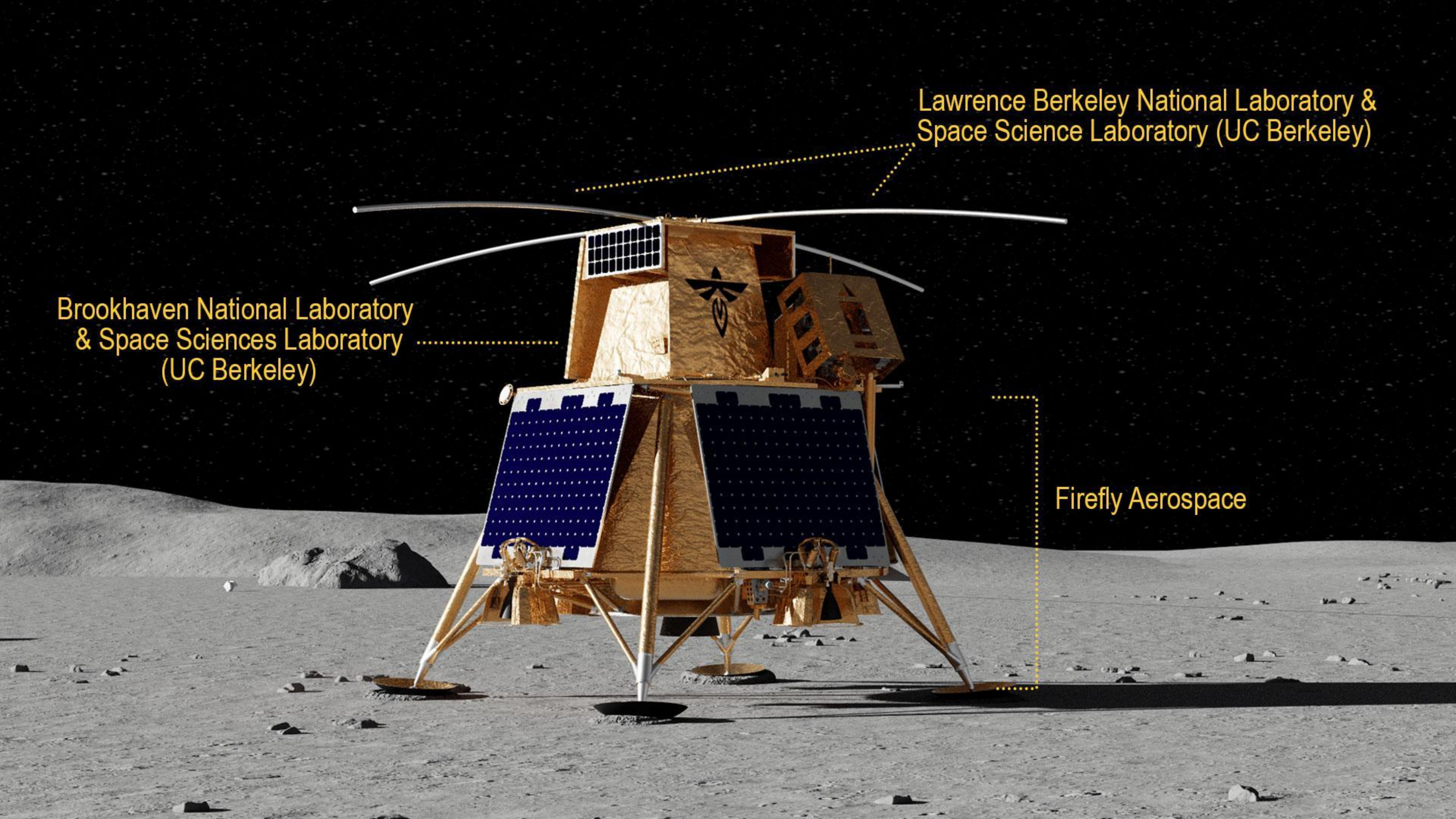


LuSEE-Night Mission.

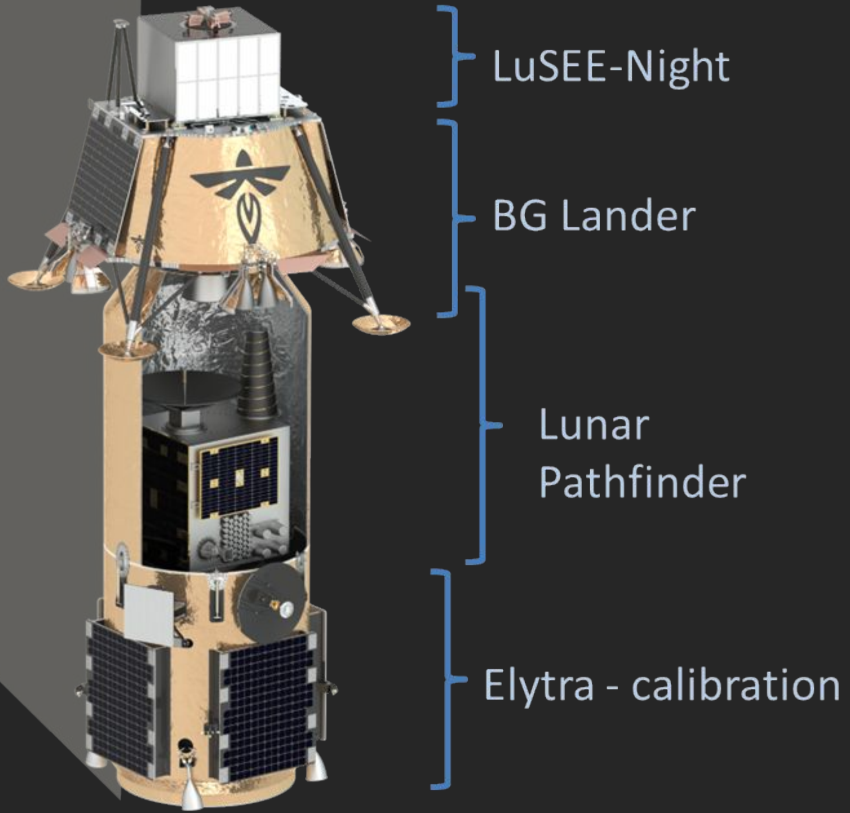
- Firefly Aerospace has been selected as the CLPS mission provider
- We will launch of CLPS CS-3 mission == Firefly Blue Ghost 2 mission
- Firefly Blue Ghost 1 was ***the sole successful CLPS mission to the Moon!***
- Launch was supposed to be Dec 2025, then summer 2026, now spring 2027
- We are the main payload, in addition:
  - “User Terminal” – a communication testbed
  - Rashid Rover (more later)


I Love
LuSEE
GSFC CU/LASP UCB/SSL UMN



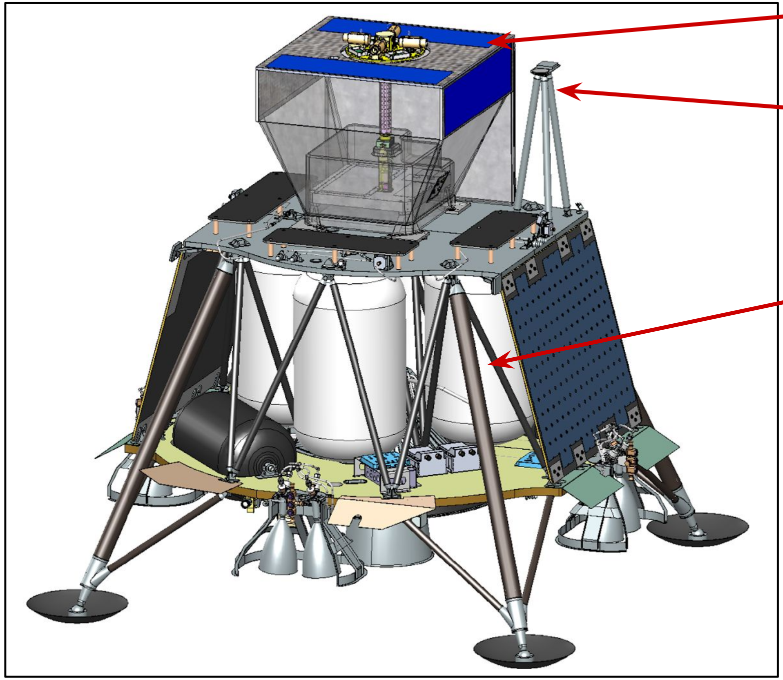

Lawrence Berkeley National Laboratory &
Space Science Laboratory (UC Berkeley)
Brookhaven National Laboratory
& Space Sciences Laboratory
(UC Berkeley)
Firefly Aerospace

SpaceX Falcon 9



Firefly Aerospace

LuSEE-Night payload on Blue Ghost 2

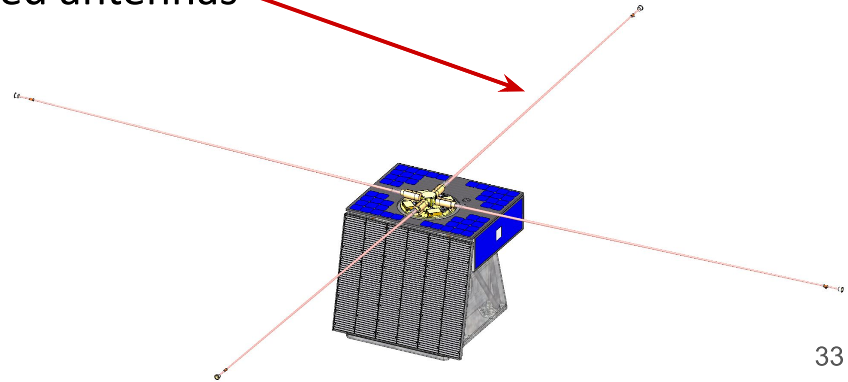


LuSEE-Night

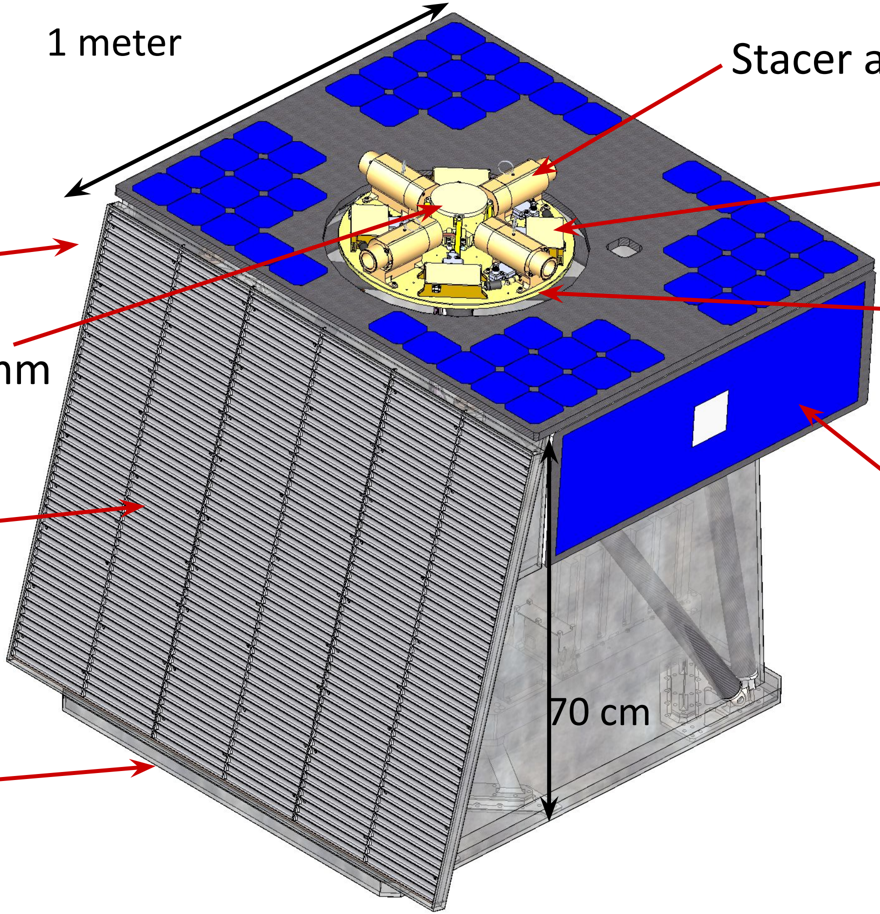
User Terminal

Blue Ghost 2

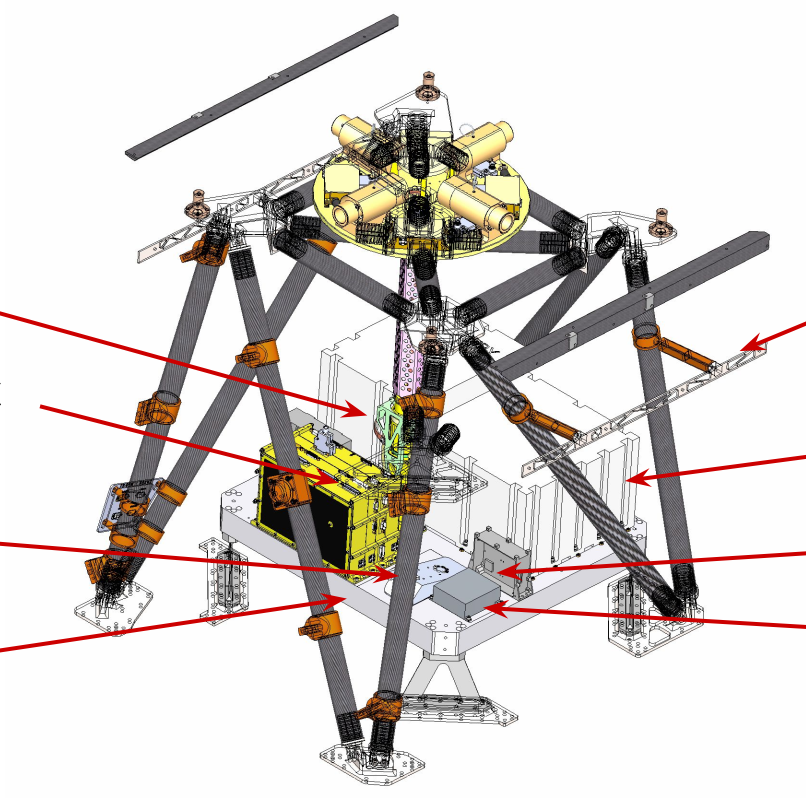
Deployed antennas



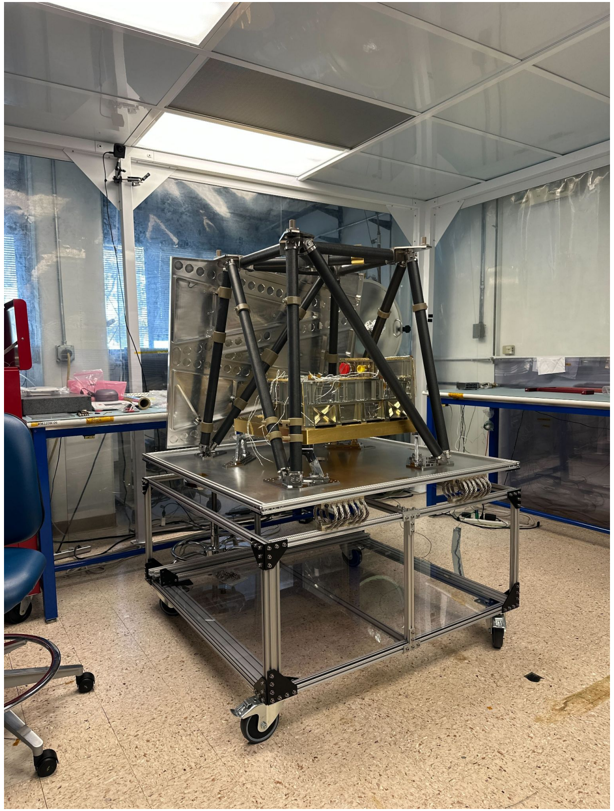
LuSEE-Night payload

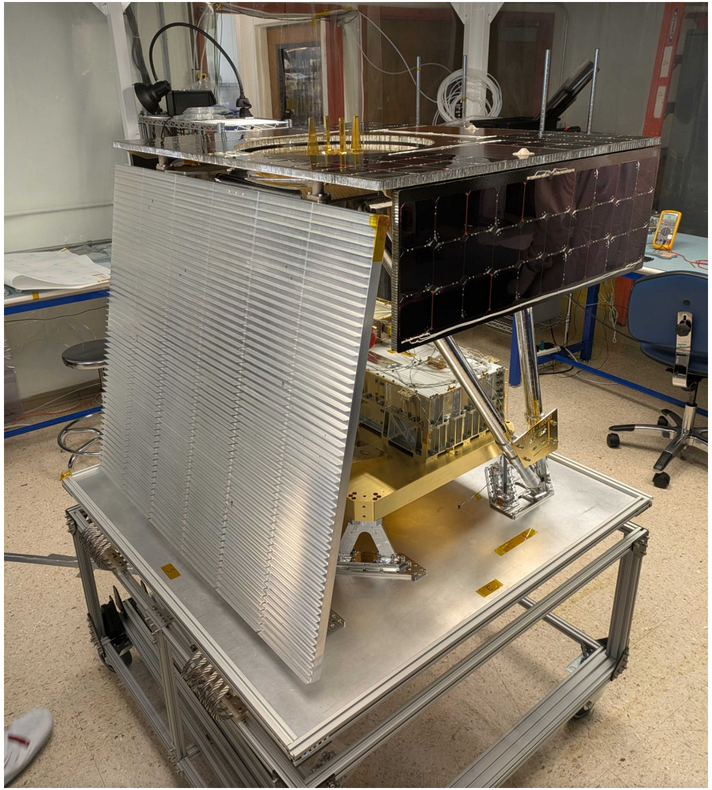


LuSEE-Night payload

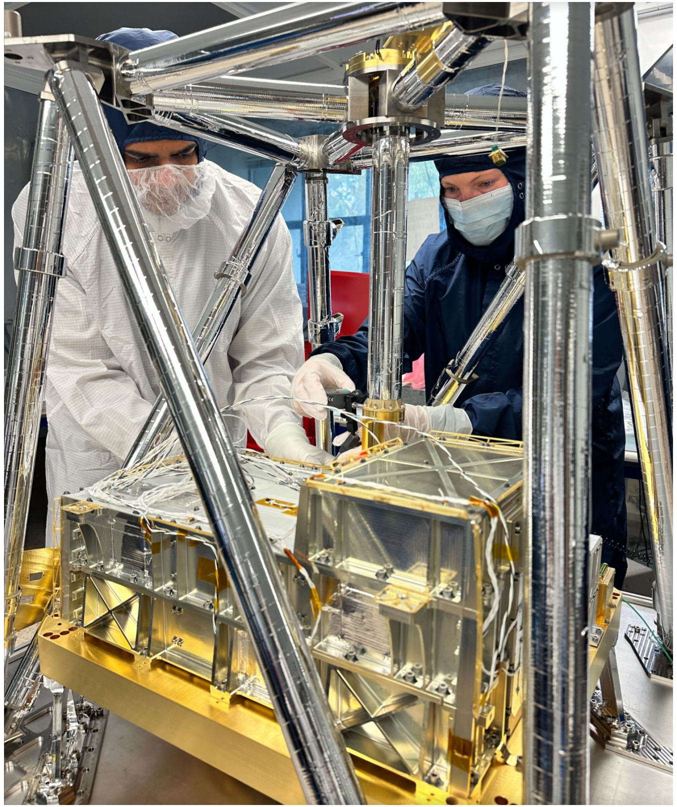


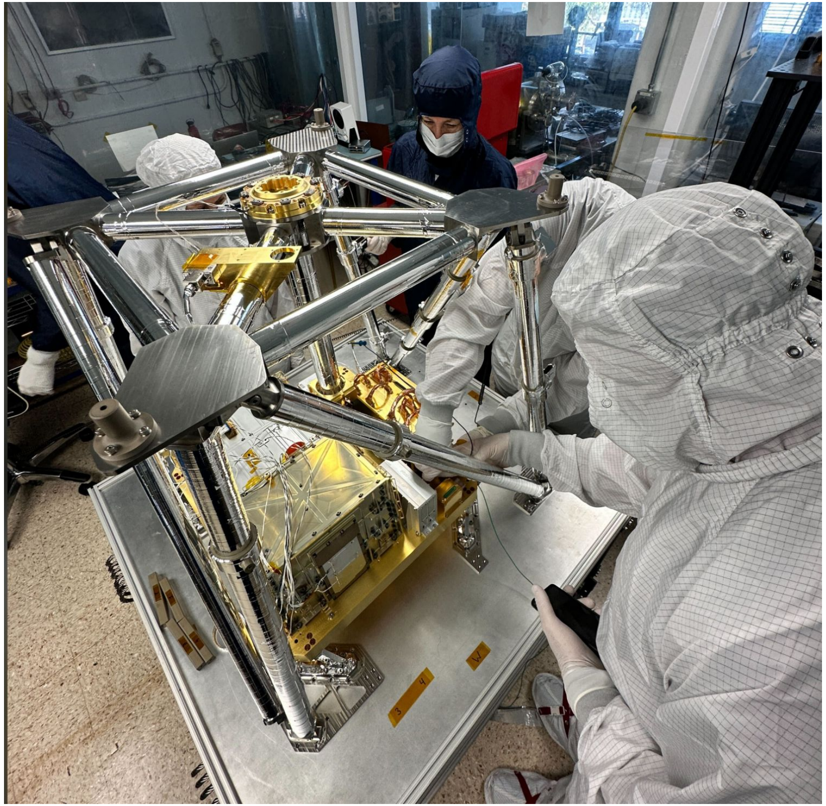
We spent a long time building it….



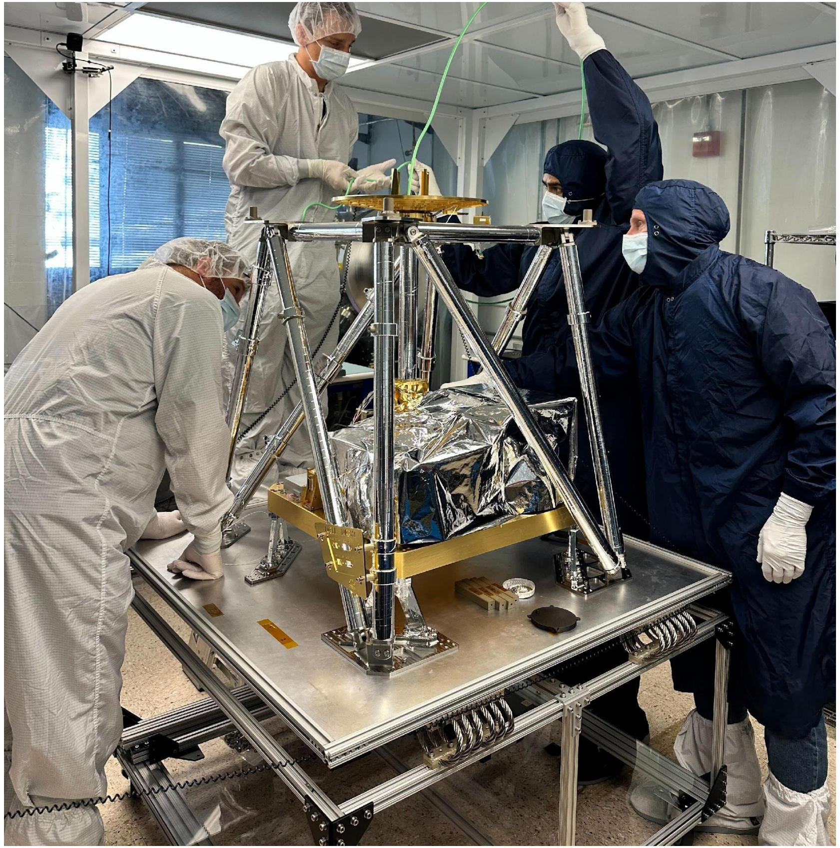


… and building it …

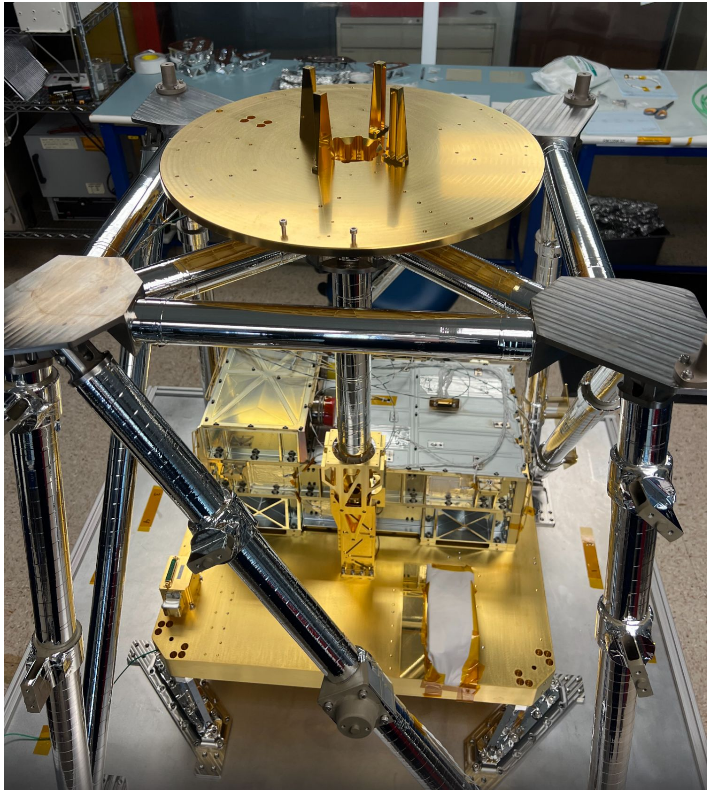


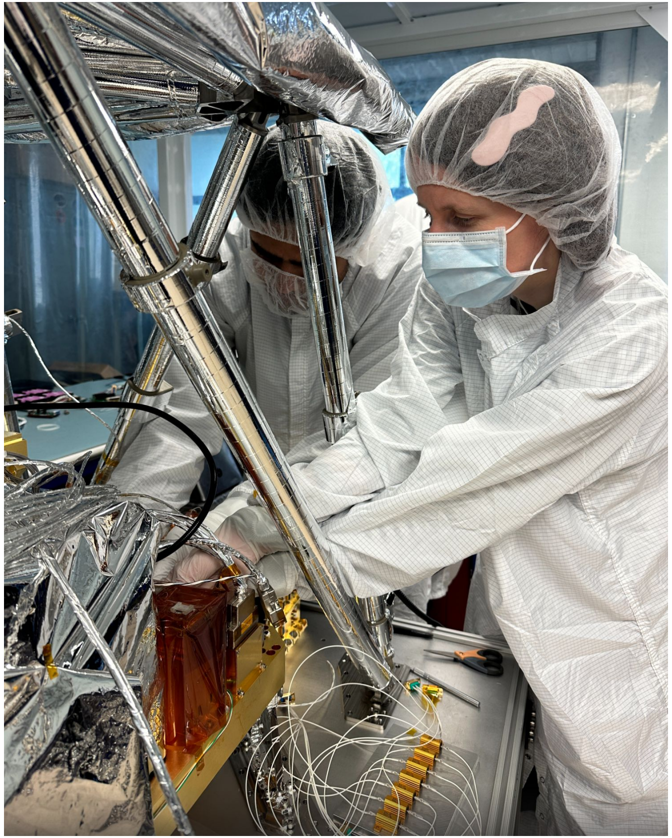


… and building it …



… and building it …



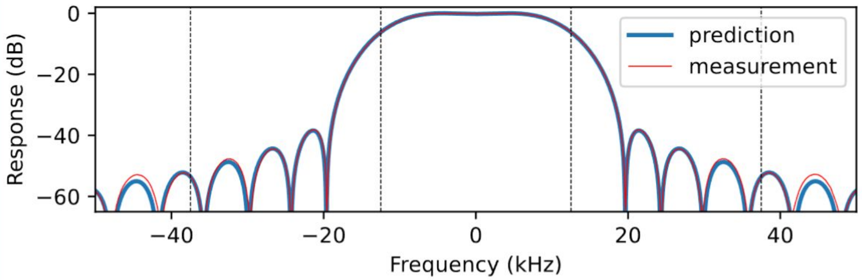


… and then we built it and shipped it!

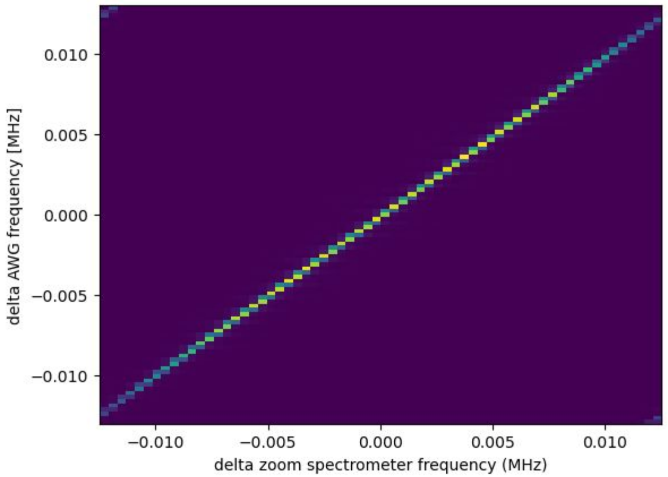
The instrument how now been accepted by the Firefly and is awaiting integration.

Spectrometer

- Spectrometer runs a fully duty cycle 51.2MHz PFB (4-taps) with 2048 channels
- Measures all 16 correlation products
- Nominal output is full resolution every 41s, but additional functionality exists:
  - automatic gain and bitslicer control
  - time-resolved spectra at 0.65s time resolution for time-domain
  - spectral zoom feature, giving 400Hz bins over limited BW
  - outlier rejection
  - scripting capability



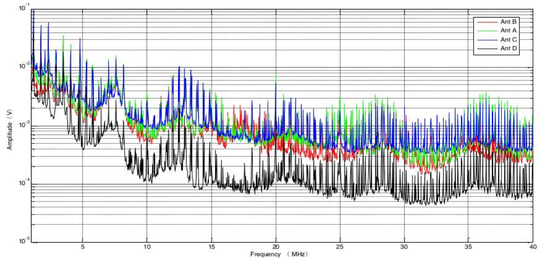
PFB response



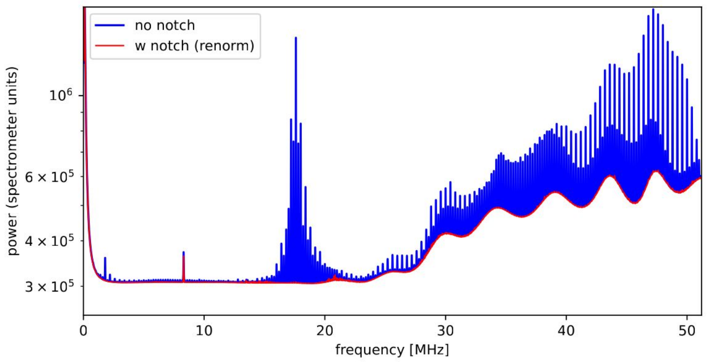
spectral zoom validation

Self-RFI control

- Self-RFI control is crucial at low frequencies
- RFI from switching power-supplies contaminates everything – radiatively and conductively
- We have strong self-RFI approach:
  - **lander dies at the end of first day**
  - All switching noise is synchronized to the same master clock
  - approach known as picket fence successfully used for Parker Solar Probe (PSP)
  - Switching noise appears only at 200kHz and harmonics
  - We can either throw away every 8th bin or use dedicated DSP notch filter in the spectrometer engine



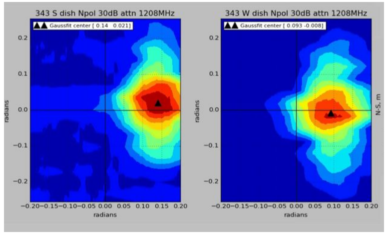
Chang’e-4 data dominated by platform RFI



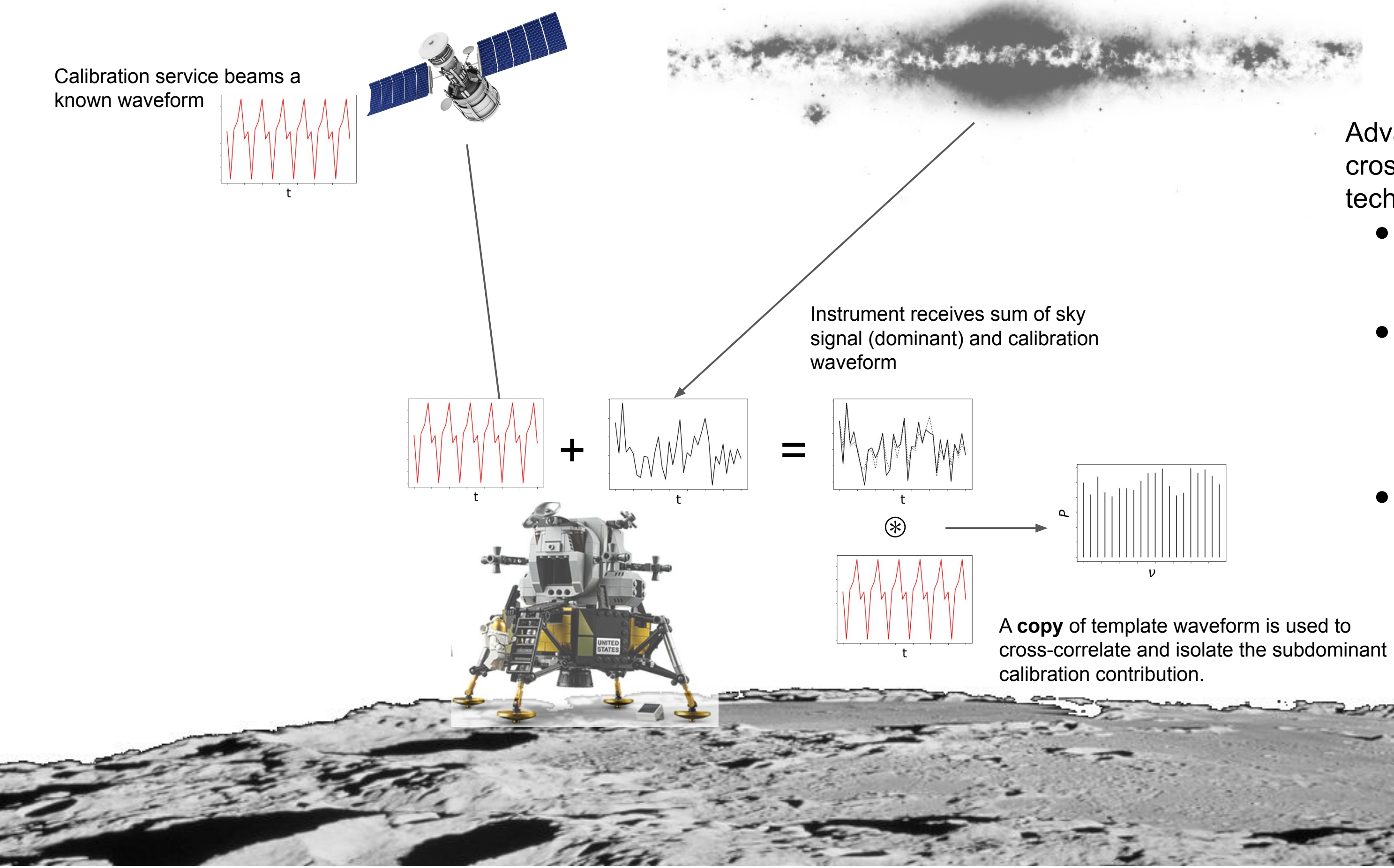
self-RFI filtering during TVAC testing

Far-field Calibrator

- Field of 21cm is a study of calibration methods
  - Foregrounds many times brighter
- Precision calibration of radio telescope beams at sub-percent precision remains to be demonstrated
- Many attempts with drones, but nobody has reached required precision
- **A true far-field, power stabilized calibrator is almost certainly necessary for dark ages work:**

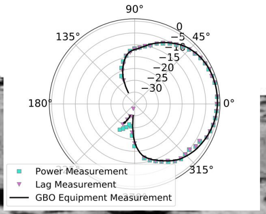


Basic Concept



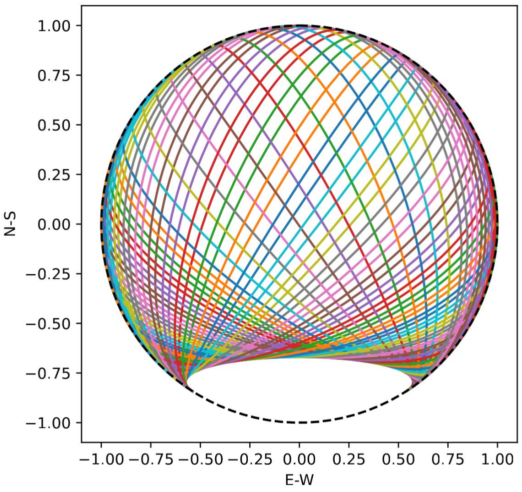
Advantages of cross-correlation technique:

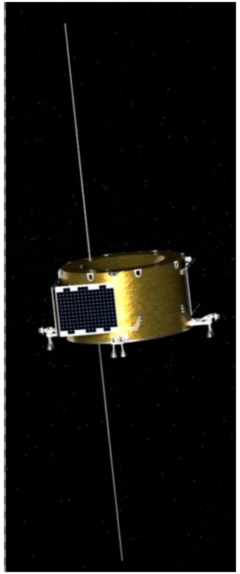
- sky background does not cross-correlate
- only one copy of template attenuated by the distance (1/r scaling), allowing high SNR recovery
- See arXiv:2201.11806 for similar approach on the ground

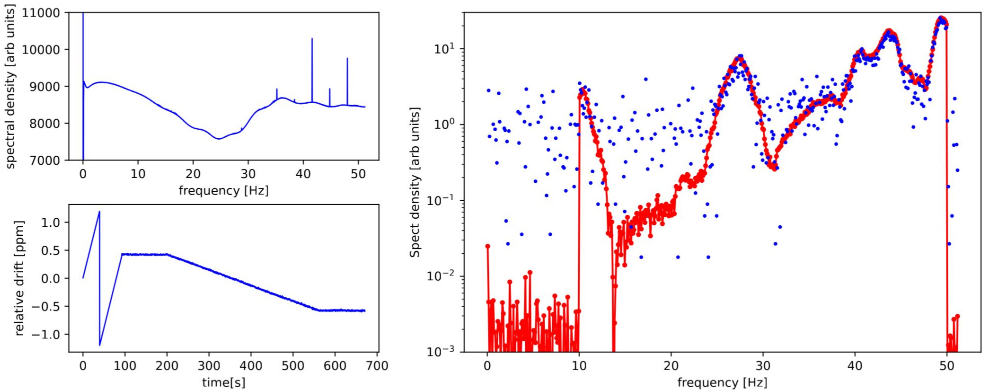


Far-field calibration

- LN will, for the first time, demonstrate calibration from a dedicated in-orbit calibrator
- Will emit 400 tones between 10 and 50MHz de-Dopplered at emission
- Spectrometer support of coherent and incoherent detection
- Source calibrated to 10% absolute with gain fluctuation a less than 1%
- Source developed by a commercial provider as a separate CLPS mission



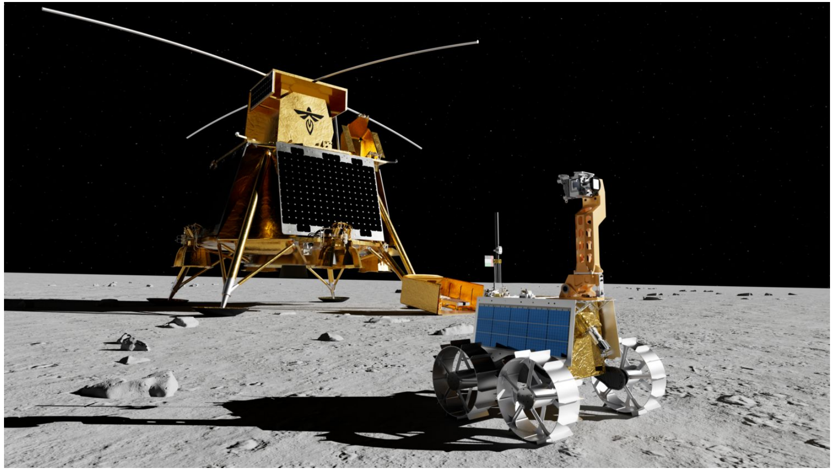


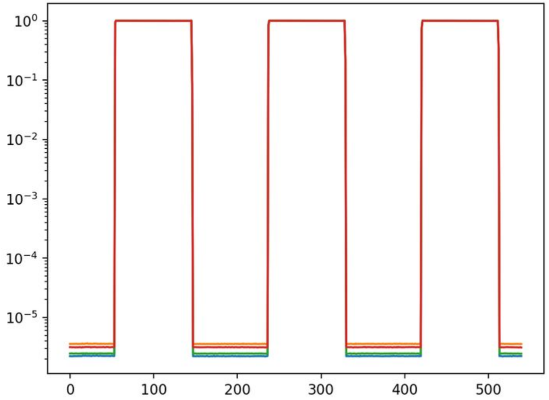


10 min integration at -30dB

Rashid Rover

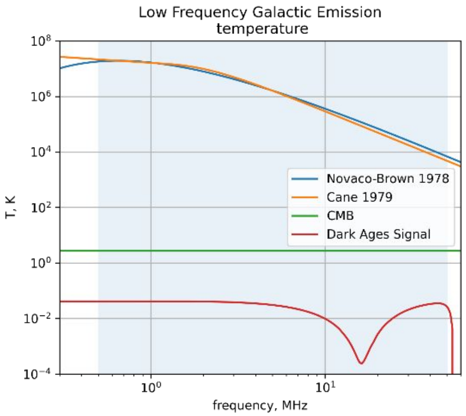
- UAE developed rover hitching a ride on Blue Ghost 2
- In collaborating with SWRI, we developed a 4 tone emitting device that will turn LuSEE+rover into a bistatic radar
- Will probe the regolith below LuSEE-Night based on interference caused by regolith layer interference



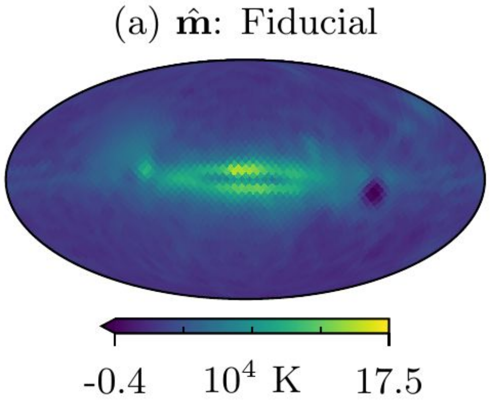


Science with LuSEE-Night

- LuSEE-Night will address a number of scientific goals spanning solar-system, astrophysics and cosmology
- It will make a low-resolution maps through data deconvolution
  - first (nearly) full-sky maps after RAE-2

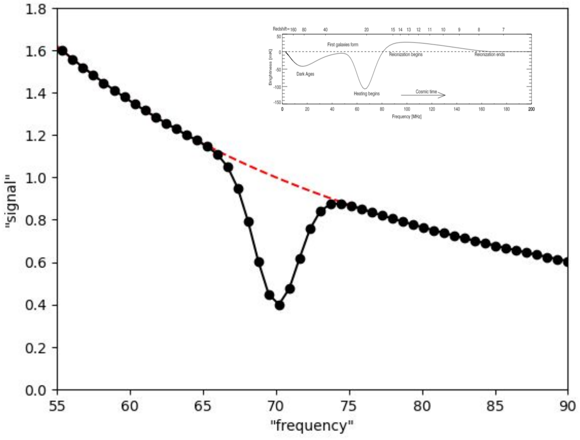


RAE-2 all sky spectrum



LuSEE-Night forecasts (Camacho et al, 2025)

Will we actually see the Dark Ages dip?



- No!
- The community has been sold on “smoothness separation”
- You can make a hand-wavy argument that it only works when

$$\frac{S}{F} \gtrsim \frac{\Delta\nu}{\nu}$$

i.e. feature is either deep or narrow

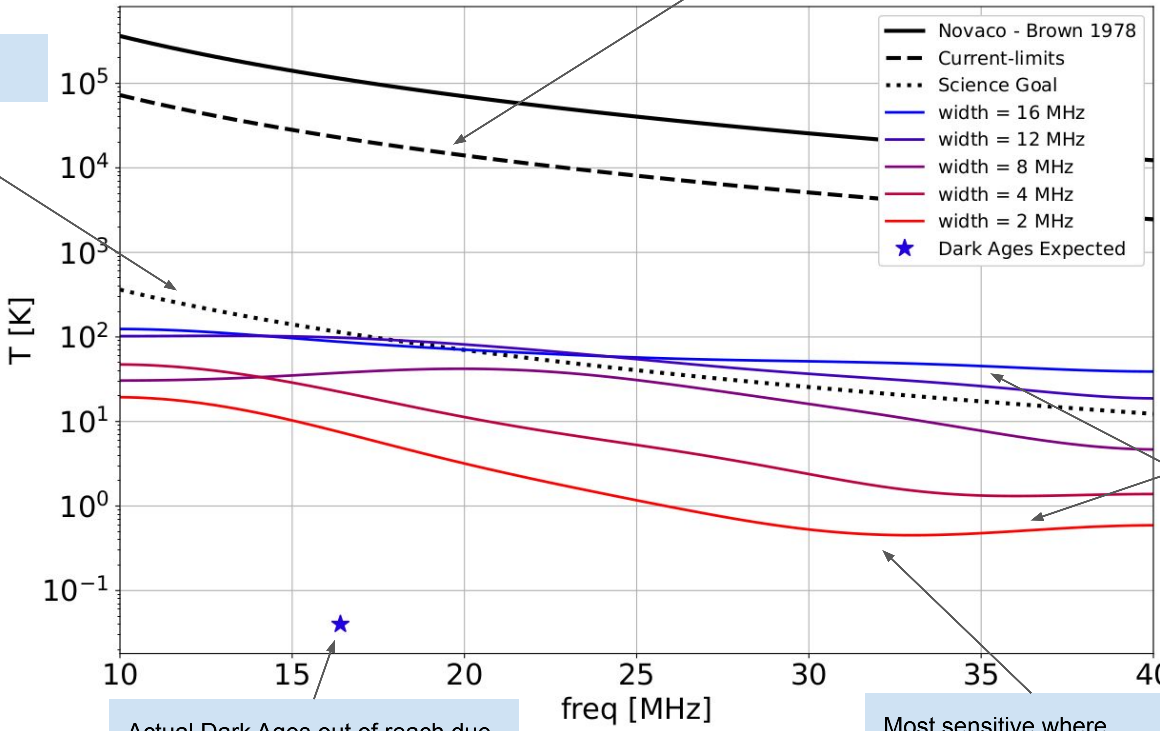
- Not true for either Dark-ages nor Cosmic Dawn signals
- My take is that you will need a high-resolution instrument in order to make it work

Signal	S/F	$\Delta\nu/\nu$	Does it work?
BAO	~0.3	~0.2	Yes, barely (but we have no-wiggle theory)
Cosmic Dawn	$\sim 10^{-3}$	~0.1	No.
Dark Ages	$\sim 10^{-5}$	~1	No No.

Sky Monopole Sensitivity plot (preliminary)

Current limits: 20% variations around Novaco - Brown

10^{-3} science goal #4



Narrow features are easier to detect since foregrounds are smooth

Actual Dark Ages out of reach due to chromaticity of dipole antennas

Most sensitive where radiometer is most sensitive

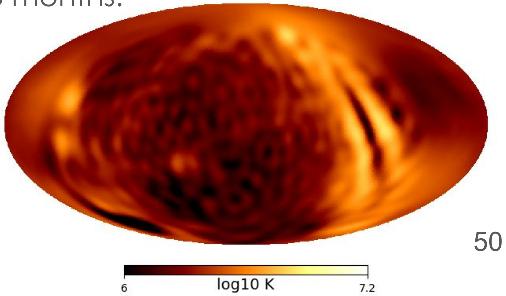
Looking Ahead

Lunar Farside Technology & Transients Telescope (LFT3)

- Take observations before RFI start to dominate
- Several bands up to 2.5 GHz
- Philanthropically funded, initiated by Breakthrough Initiatives
- David DeBoer is the PI, AS Spectrometer subsystem lead
- Compared to LuSEE-Night:
  - a lot of focus on time-domain and techno-signature search
  - would have a dedicated lander
  - being philanthropic it is driven by somewhat different considerations

FIORE (Farside Interferometry Occultation and Regolith Experimen)

- Proposal to NASA PRIM call
- PI Stuart Bale (SSL), AS institutional PI
- Continuation of LuSEE-Night, but this time demonstrating **interferometry to 1.5km**
- Additional science focused on regolith (**RadICE** GPR instrument)
- Will use combination of horizontal and vertical antennas
- Vertical antennas will demonstrate a novel **horizon occultation imaging**
- Will use CLPS mobility to put a second element on the rover
- Signal /clock transport by **laser comms**:
  - Several Gbps
  - led by UK Northumbria group
- Proposal due in 3 months.



Conclusions

- LuSEE-Night will land early 2027
- It will:
  - perform ground-breaking measurements at <50MHz
  - demonstrate lunar far-side as a radio observatory
  - demonstrate a number of technologies required to push the field forward
- Further experiments already under development:
  - FIORE/RADICE
  - LFT3
- Stay tuned!
- Get in touch!