

A Vision for 21-cm Hydrogen Cosmology from the Far Side of the Moon

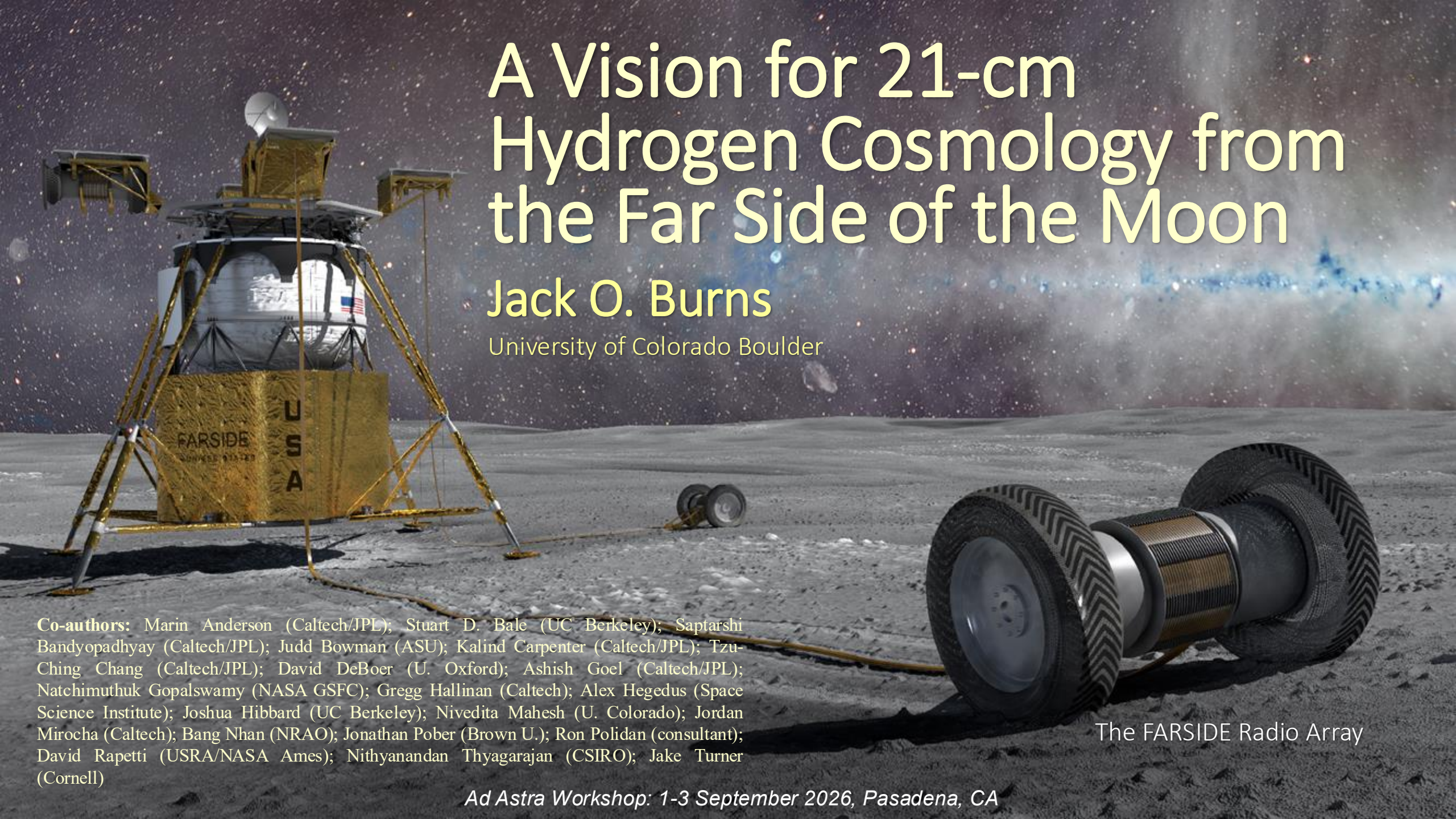
Jack O. Burns

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Ad Astra Workshop: 1-3 September 2026, Pasadena, CA

The FARSIDE Radio Array



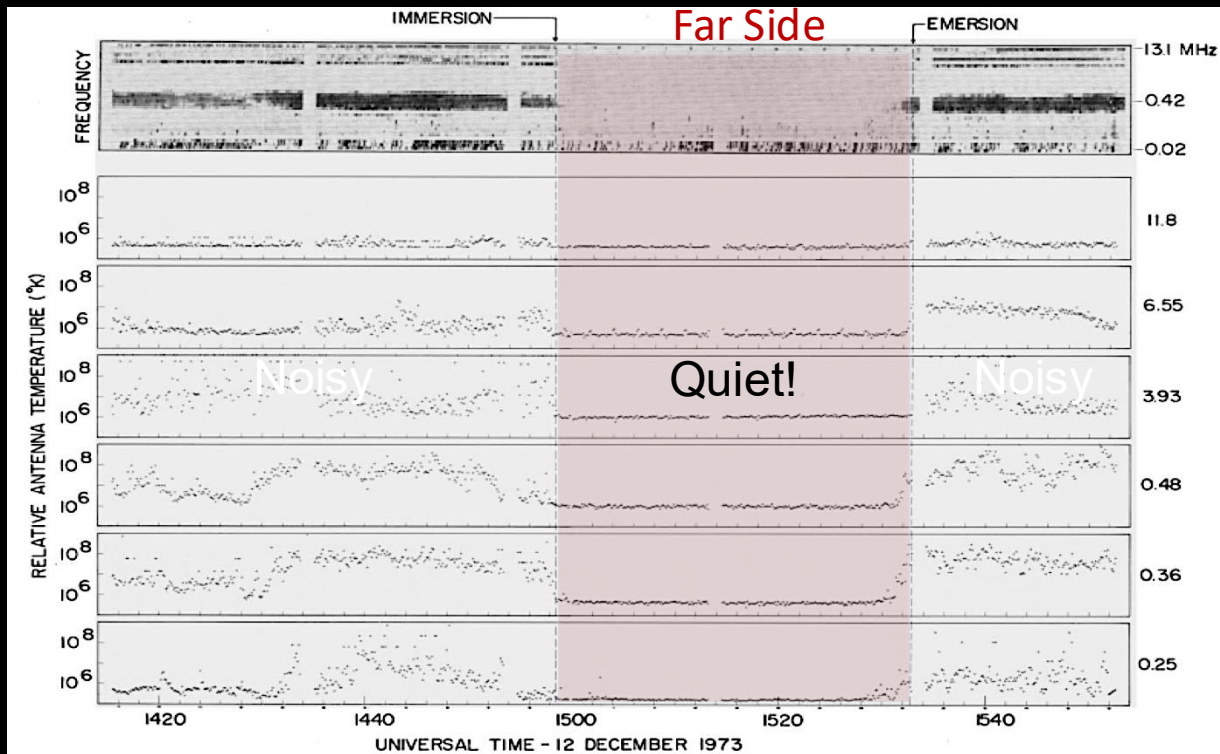
How Does the Universe Work?

Lunar Far Side at Low Radio Frequencies

The last unopened window in the electromagnetic spectrum is at low radio frequencies, especially 0.1-50 MHz. This window is fully accessible from the lunar far side which lacks an ionosphere and is shielded from anthropogenic RFI. Embedded within this window is a unique unexplored epoch of the Universe – the Dark Ages – before the first stars and galaxies formed. The structural evolution is linear and the epoch is pristine without stellar astrophysics. **This is where physics beyond the standard model – dark matter interactions, early dark energy, inflationary non-Gaussianity – will be revealed!**

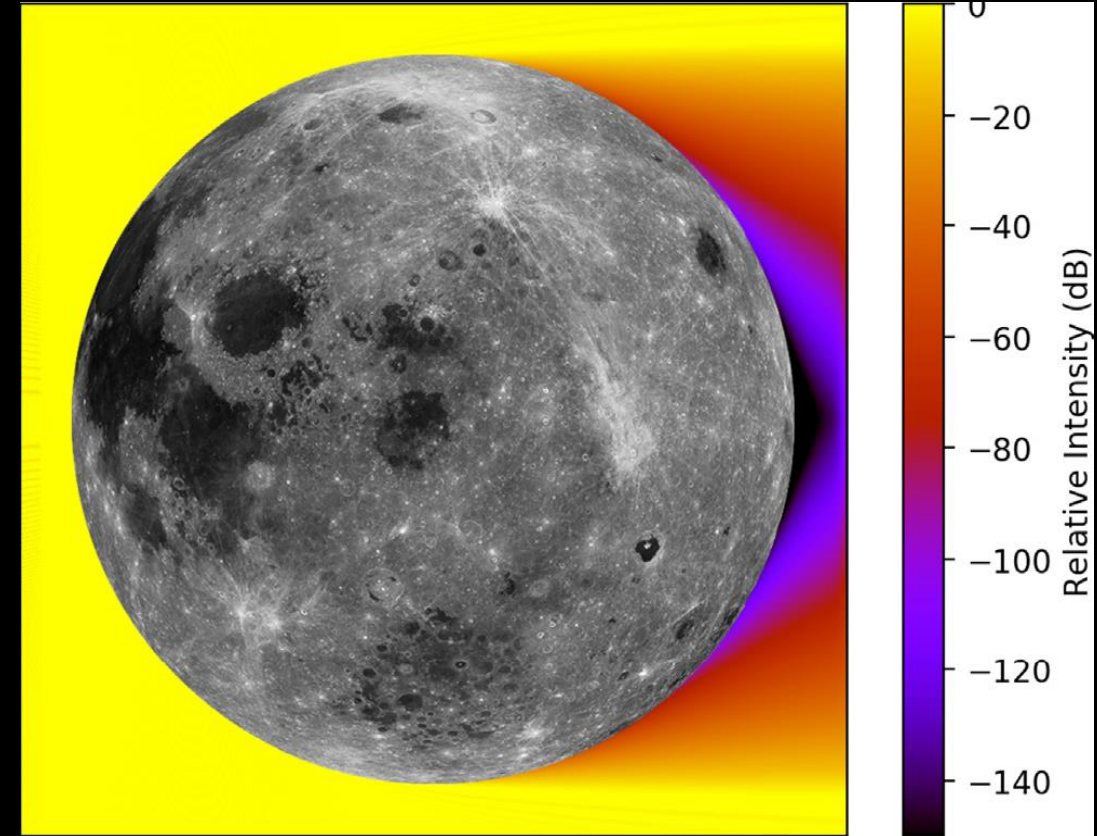
The Lunar Far Side is Uniquely Quiet

- The Moon lacks any substantial ionosphere (plasma frequency ~ 60 kHz).
- Proven, uniquely radio-quiet on the far side.



From NASA's RAE-2 lunar orbiter. Alexander et al. 1975, *Astronomy and Astrophysics*, 40, 365-371.

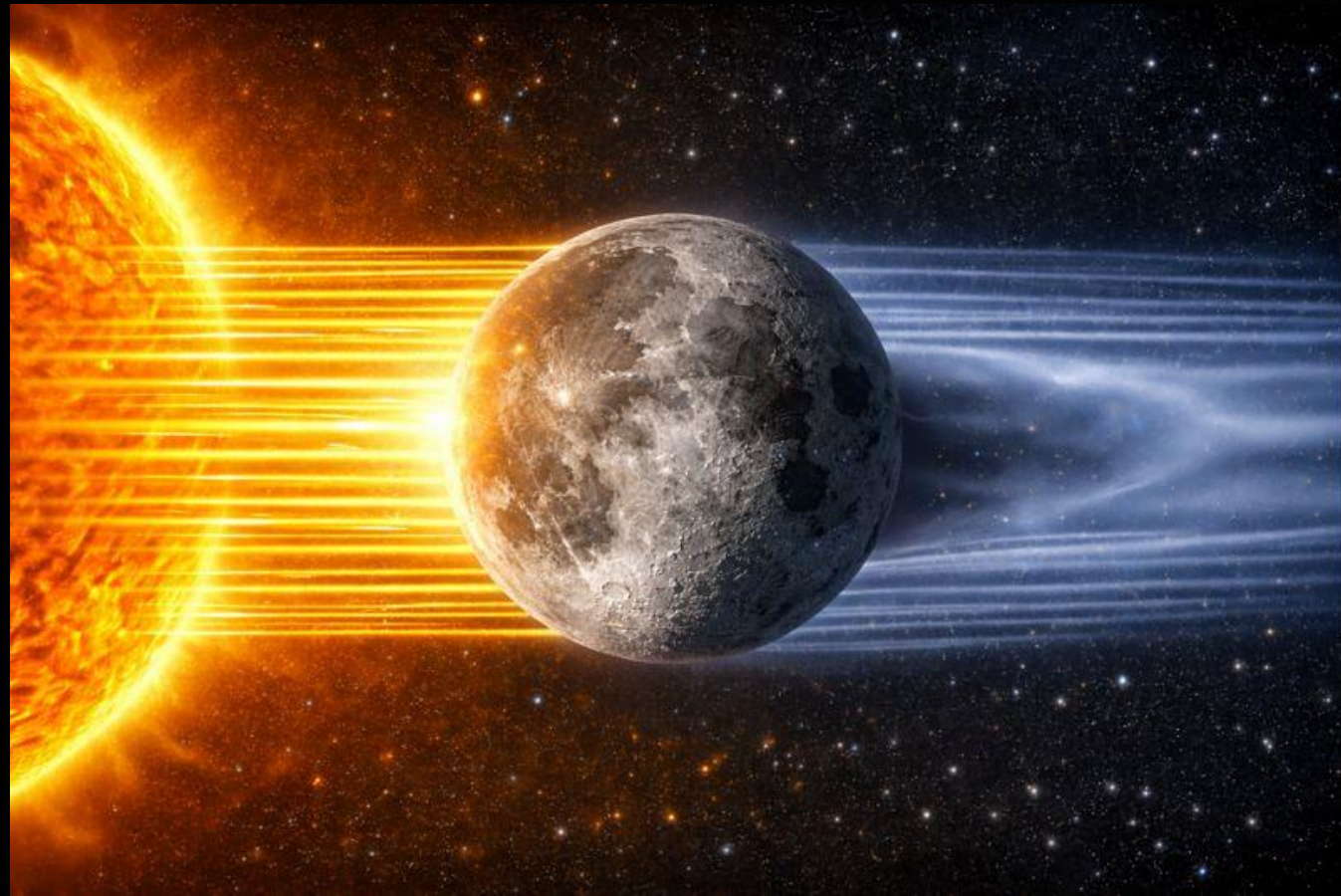
Numerical Modelling of the Radio-Quiet Zone on the Lunar Far Side



Results of a 4000 x 4000 km FDTD simulation at 30 kHz. RFI incident from the left is attenuated behind the Moon on the right. Bassett, Rapetti, Burns et al. 2020, *Ad. Space Research*, 66, 1265.

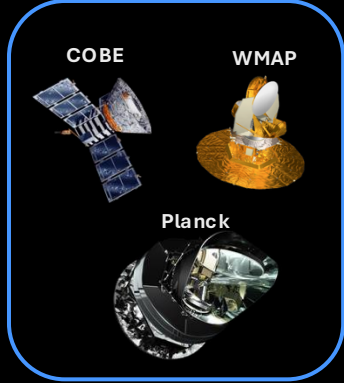
Why the Moon and Why the Far Side?

- Unlike the Earth, the Moon has a dry and stable surface and subsurface that does not change with time. This simplifies the EM coupling of the radio beam with the dielectric below the surface.
- The lunar far side at night is shielded from the solar wind, especially in the wake cavity. This minimizes quasi-thermal noise.



The solar wind is shielded within a wake above the far side at lunar night.

Cosmic Microwave Background

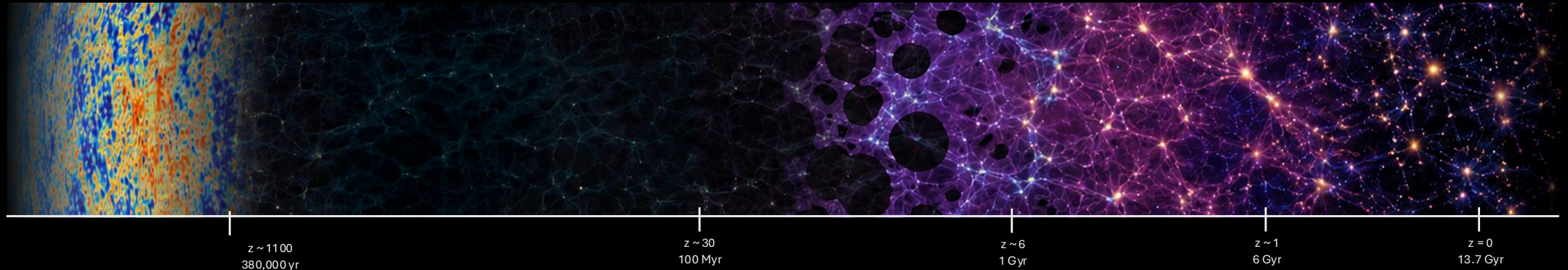
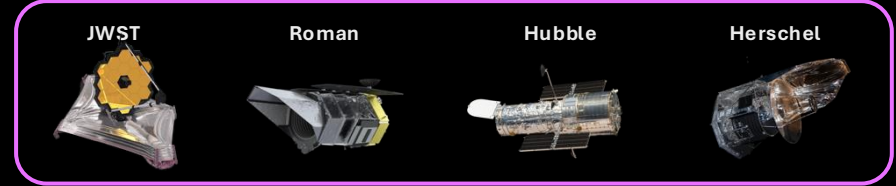


No data
on cosmic structure
during the Dark Ages.

Low Frequency Earth-based Radio Interferometers

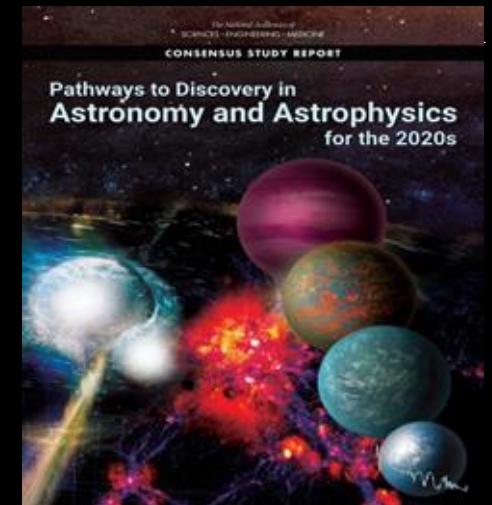


Space Telescopes (optical/IR)



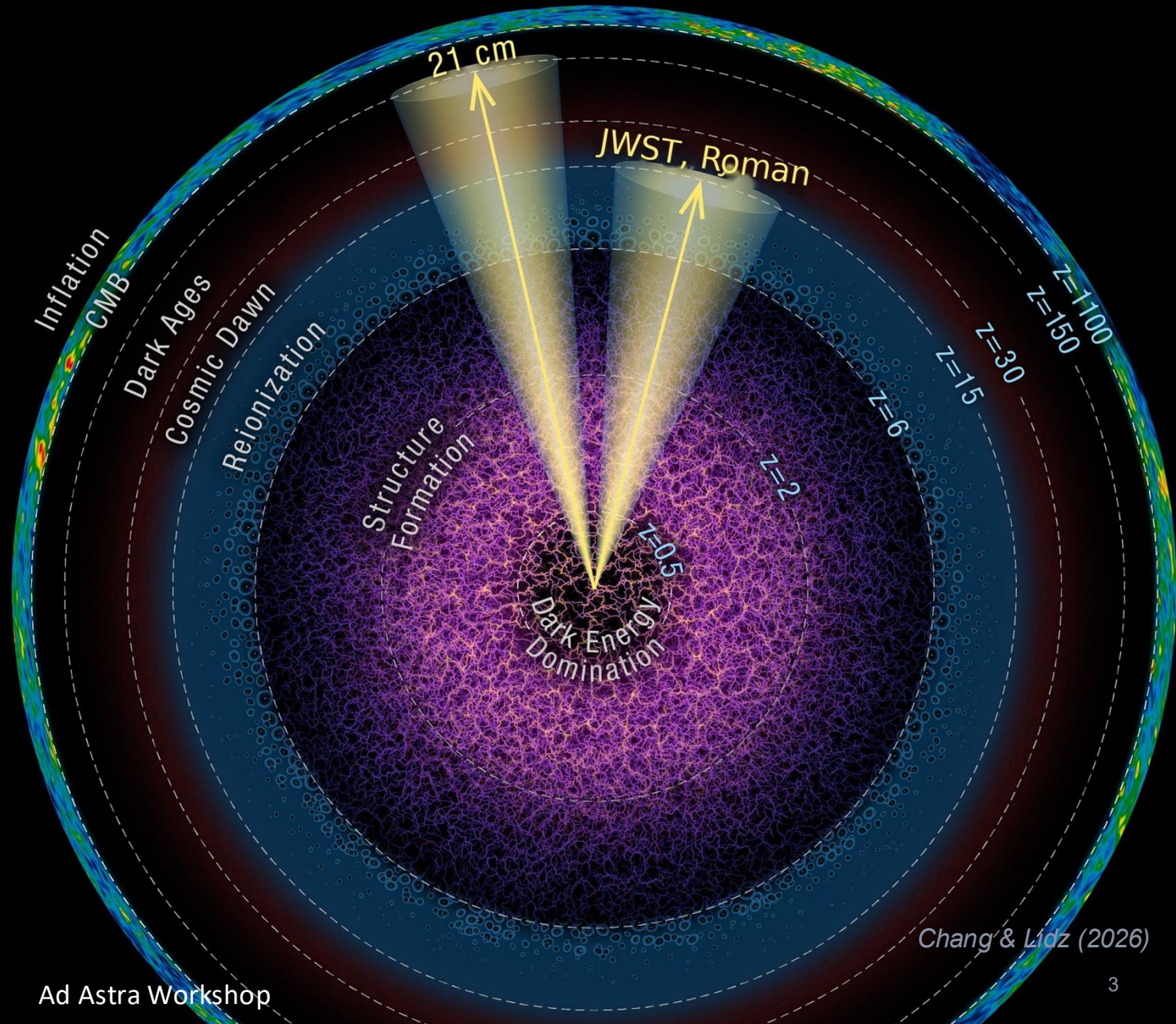
The Astro2020 Decadal Survey cosmology panel singled out the Dark Ages as the **top priority Discovery Area in Cosmology**.

The 21-cm hyperfine line of neutral hydrogen is the **only known probe** of this pristine, largely-linear era — **inaccessible to JWST, Roman, HERA, or any planned facility**.



21-cm Cosmology

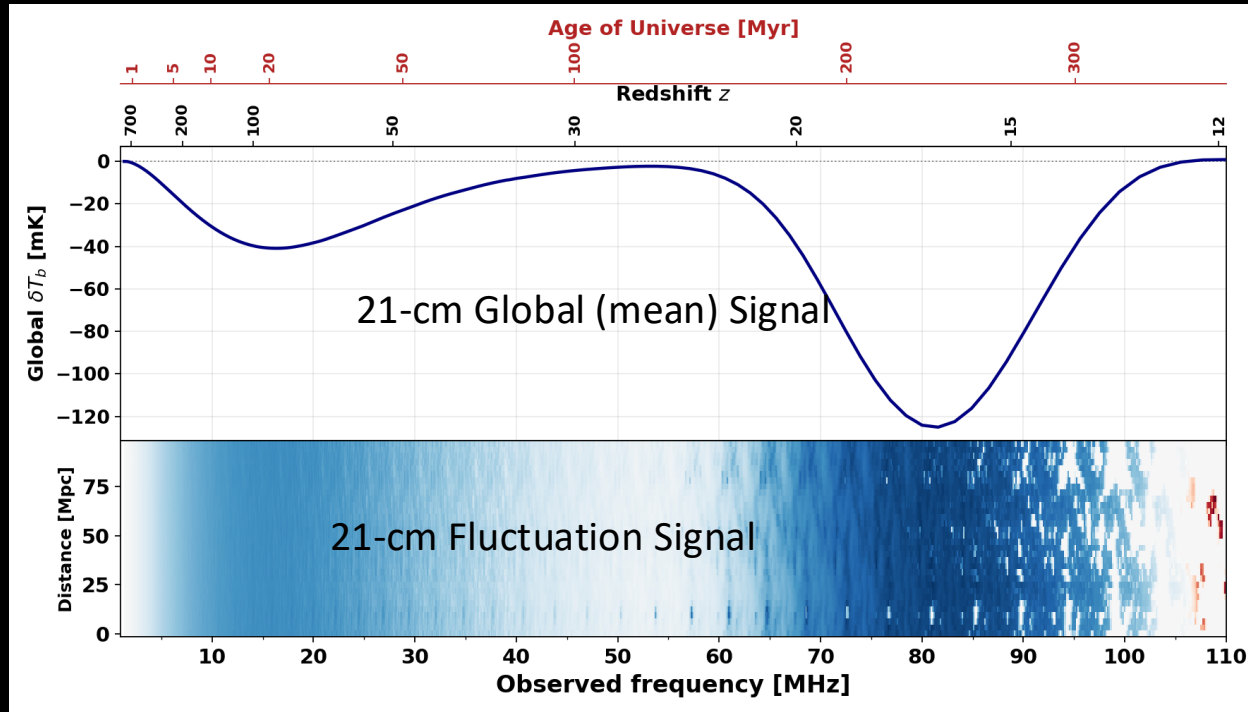
- The Dark Ages is the last frontier in Cosmology. It provides a pristine testbed with unparalleled statistical constraining power compared to CMB and galaxy surveys
 - Enable precision constraints on dark matter models and cosmic inflation
 - Constrain early dynamical dark energy
 - Dark Ages provides a 3-D map of linear density fluctuations across redshift $z \sim 30\text{--}100$.
- The 21-cm Cosmic Dawn signal is uniquely sensitive to the onset of the first stars and first black holes



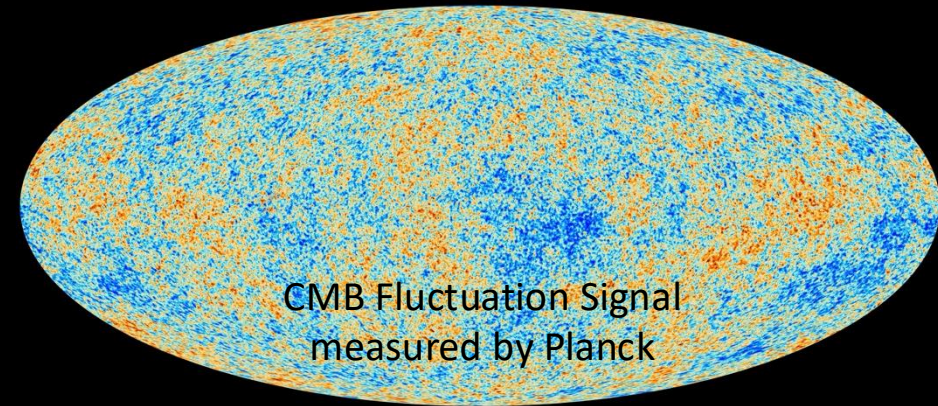
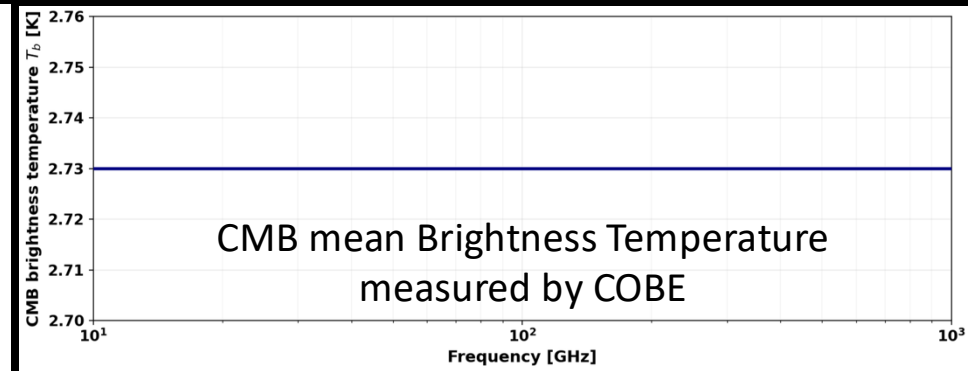
Chang & Lidz (2026)

21-cm vs the Cosmic Microwave Background (CMB): Global and Fluctuation Signals

21-cm Dark Ages
3D Cosmic Web, 10^{11-17} modes

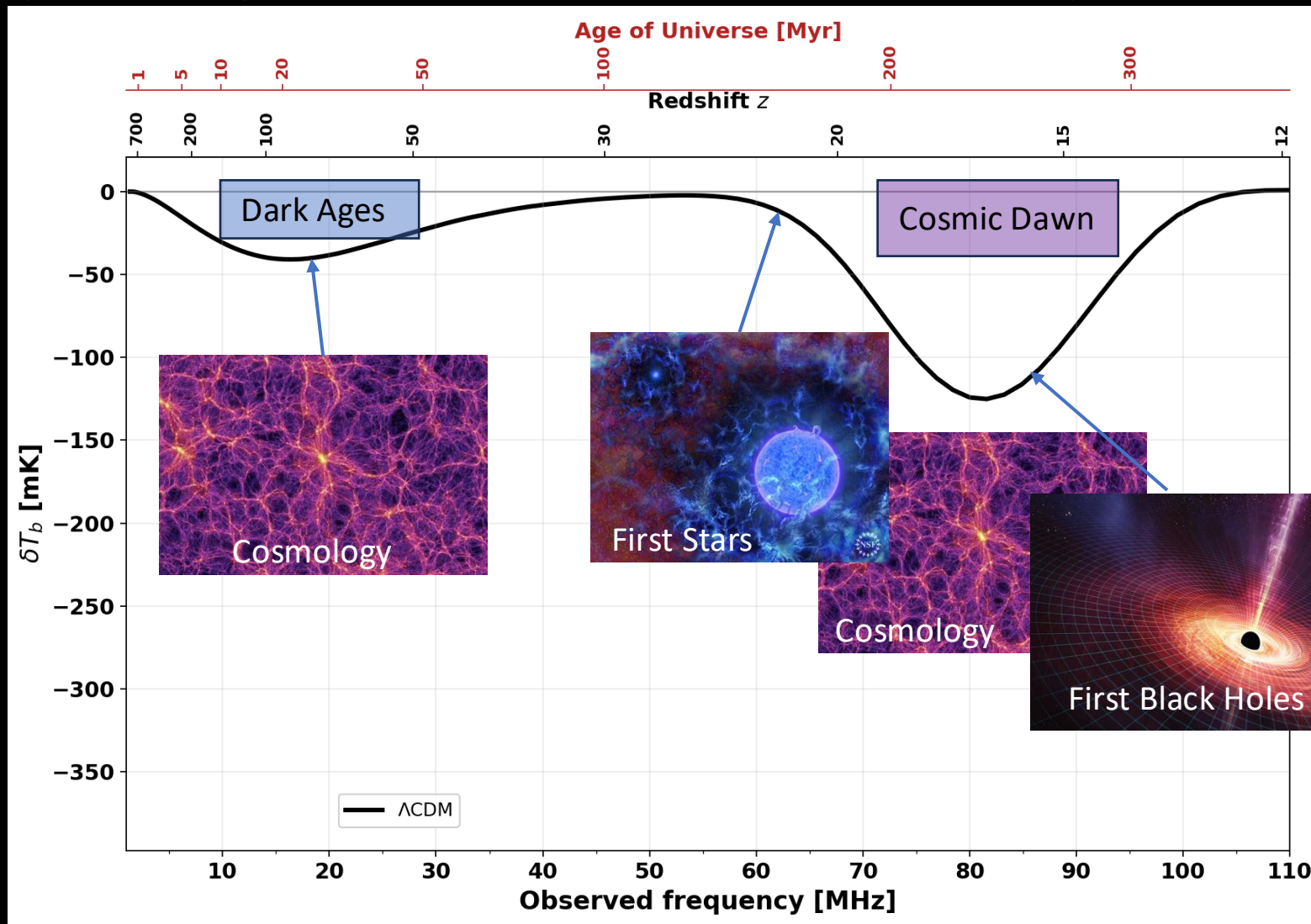


CMB (limited by Silk Damping)
2D fluctuations surface, 10^{6-7} modes

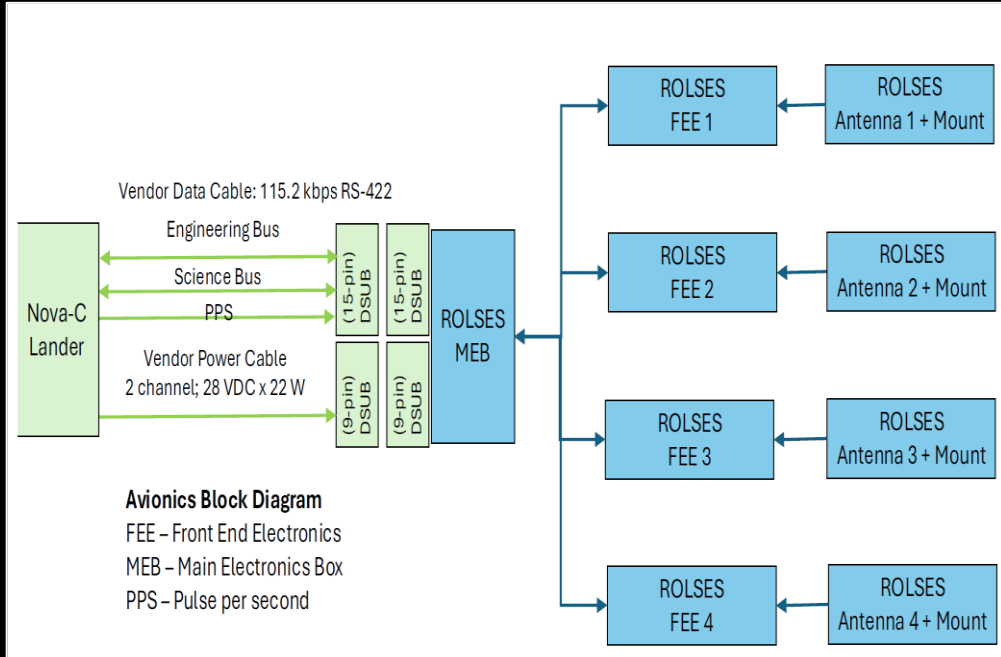


Enormous mode count enables exquisite statistical power to test fundamental physics, including the nature of dark matter, the small-scale matter power spectrum, and the structure of inflationary perturbations, with unprecedented precision.

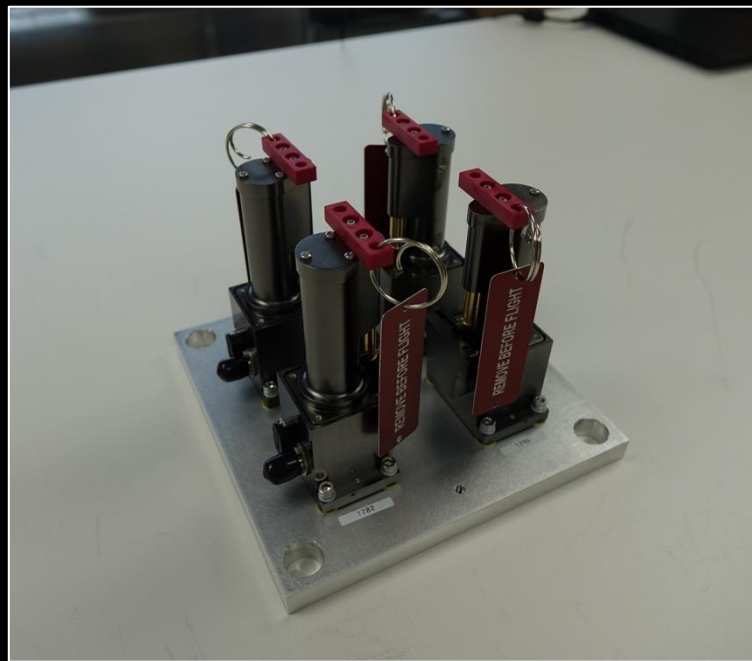
Exploring the Undiscovered Early Universe



$$\delta T_b \simeq 27 \bar{x}_{\text{HI}} (1 + \delta) \left(\frac{\Omega_{b,0} h^2}{0.023} \right) \left(\frac{0.15}{\Omega_{m,0} h^2} \frac{1+z}{10} \right)^{1/2} \left(1 - \frac{T_R}{T_S} \right) \text{ mK}$$



ROLSES-1 Block Diagram



Stowed STACER antennas



ROLSES spectrometer board

NASA's First Radio Telescope on the Moon:

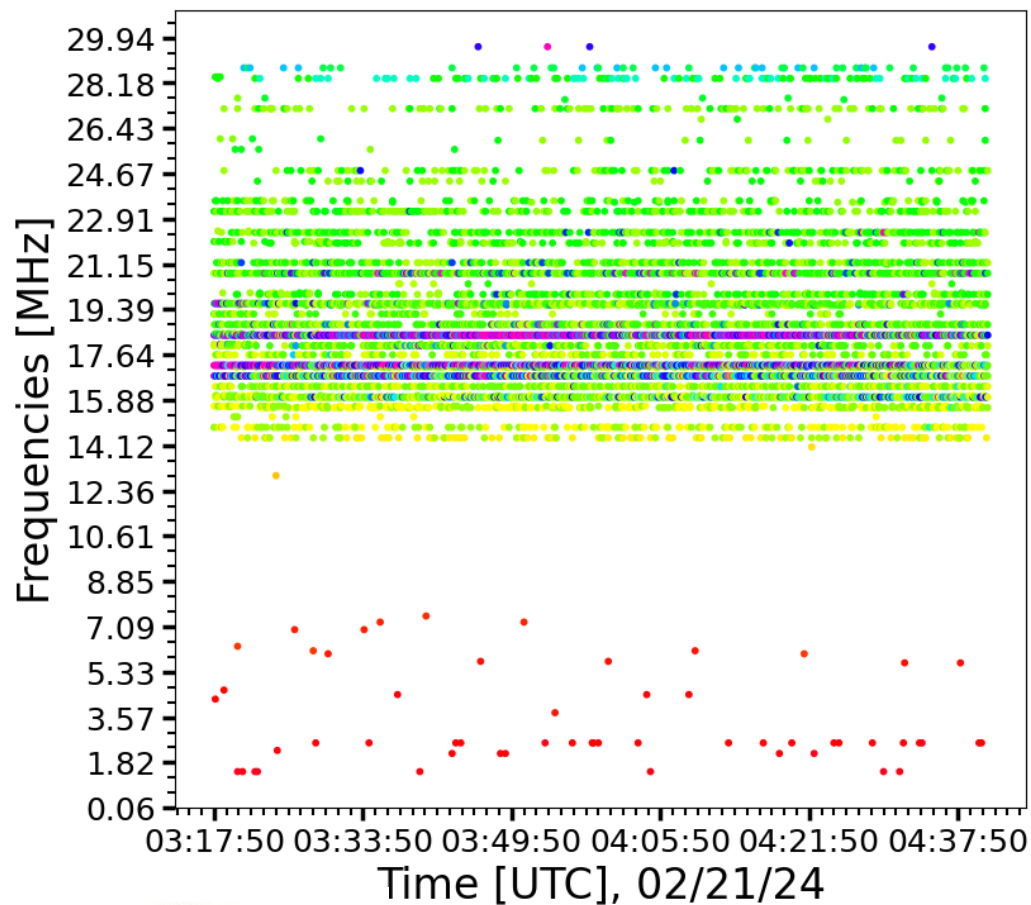
Radio wave Observations at the Lunar Surface of the Electron Sheath (ROLSES)

- **ROLSES Team:** N. Gopalswamy (PI), J. Burns, R. MacDowall, W. Farrell, D. Bradley, M. Reiner, D. McGlone, M. Choi, S. Murphy, R. Katz, I. Kleyner, D. Rapetti, J. Hibbard, J. Dorigo Jones.
- **ROLSES instrument** is a new build with heritage from NASA SMAP Earth Remote Sensing satellite:
 - Four 2.5-m monopole antennas.
 - Radio spectrometer with 2 bands:
10 kHz – 1 MHz and 10 300 kHz – 30 MHz.
- **Landed near-side, South Pole region, Feb. 2024.**

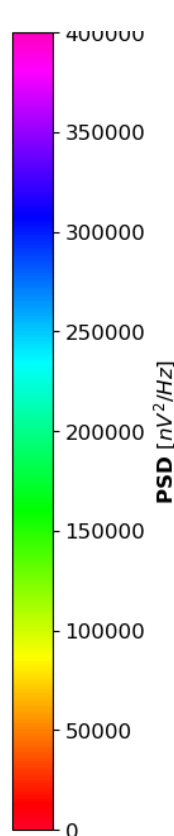
Odysseus Lander
inside the fairing of
the SpaceX Falcon
9 rocket

ROLSES
Antenna
Housing

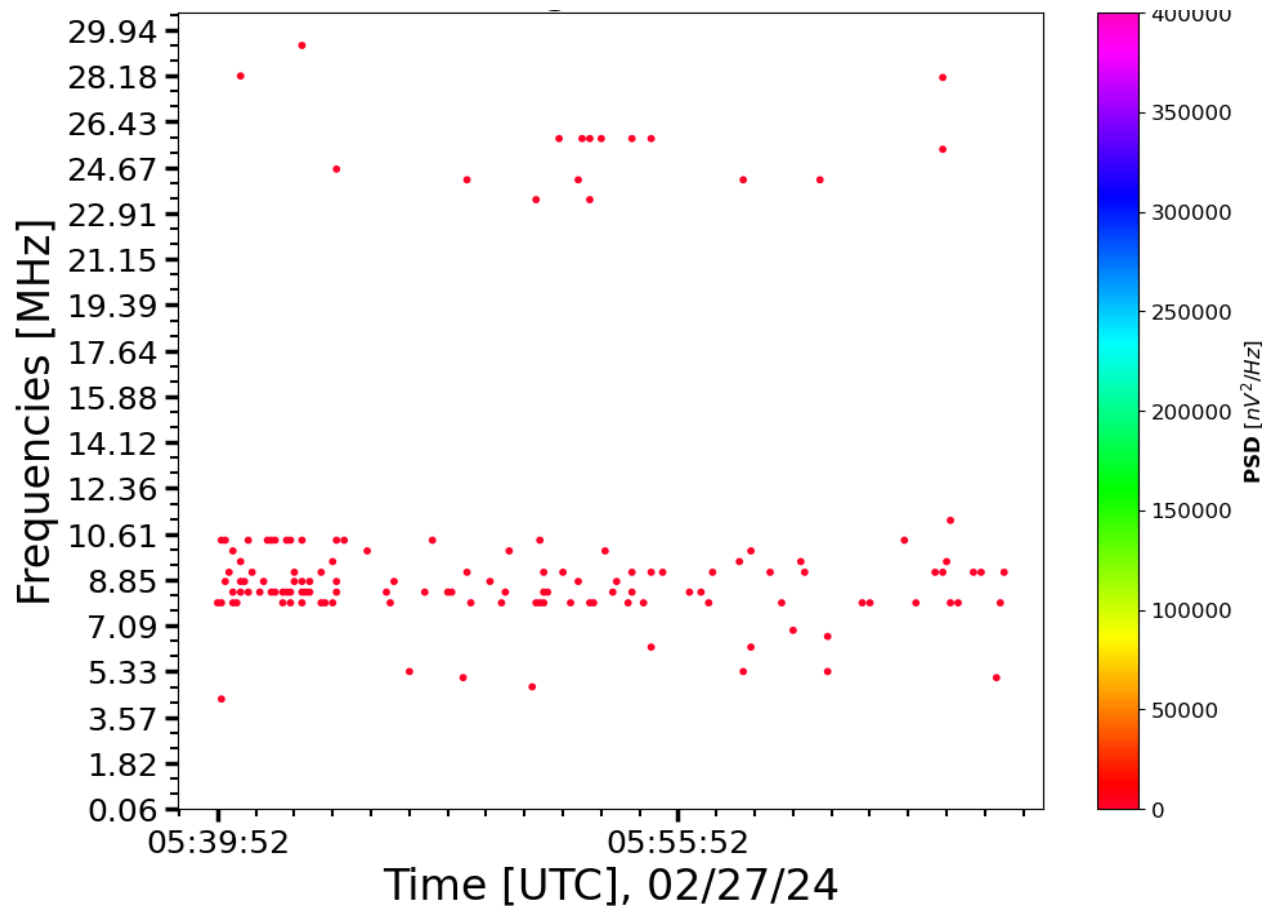
In-Transit, Calibrated, Cleaned



Technosignatures



Lunar Surface, Calibrated, Cleaned



Clear, good S/N measurements of Human-made Earth Transmissions

- Instrument frequency bandwidth corrections applied
- Flagged channels with internal EM interference
- Corrected for instrumental shelf noise



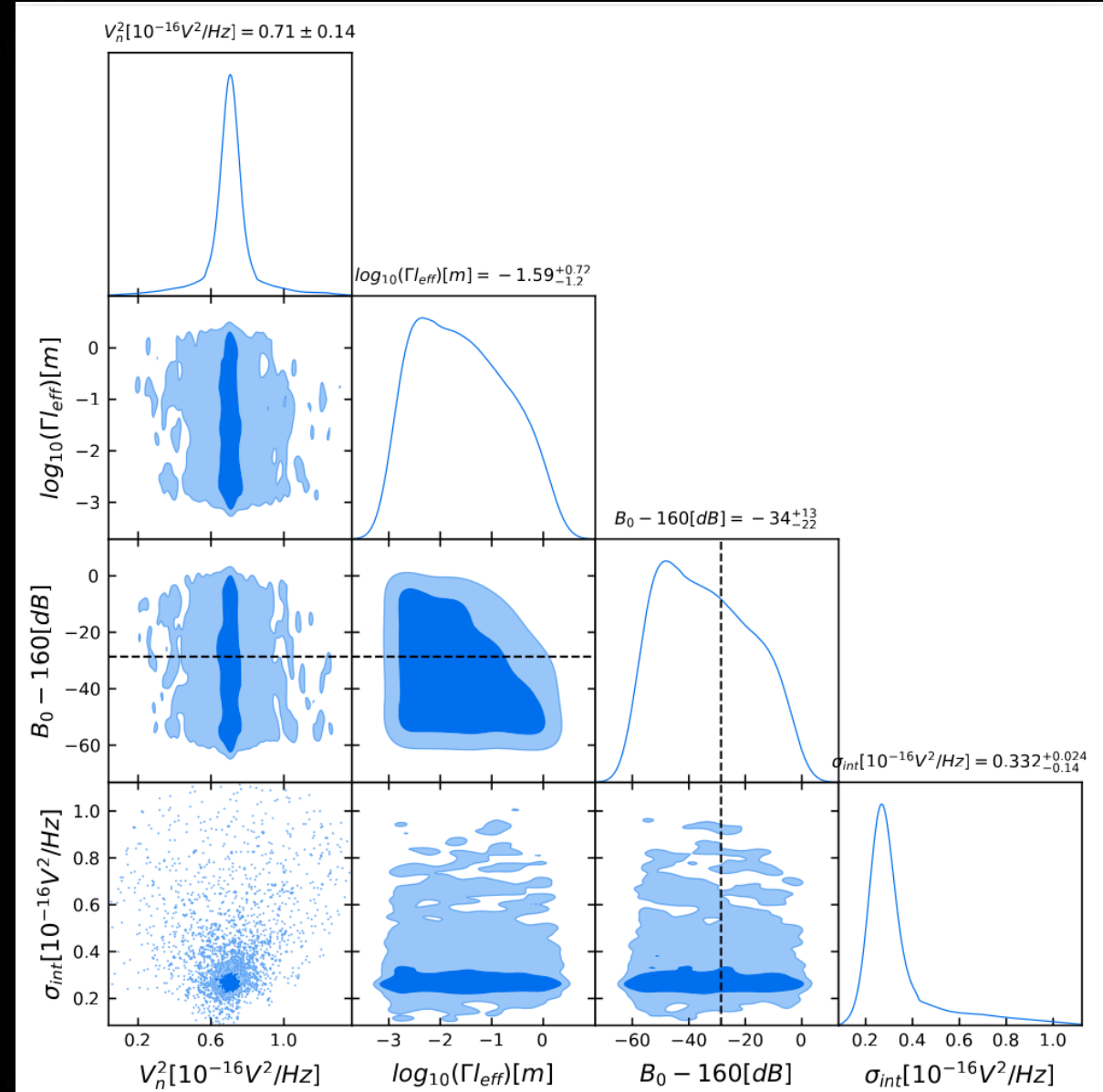
First Detection of the Galaxy from the Moon

Parameter Constraints

$$V_r^2 = V_{\text{noise}}^2 + \frac{2\pi}{3} Z_0 \Gamma^2 l_{\text{eff}}^2 B_\nu(\nu)$$

where Z_0 is the impedance, Γ is antenna efficiency, l_{eff} is the effective length of the antenna, and B is the Galaxy brightness

- At different levels of frequency averaging, there is a *slight* preference for a model with the Galactic spectrum over one without (comparing KS-test p-values).
- Black dashed line shows the expected value of the Galactic amplitude from the Novaco and Brown 1978 spectrum.

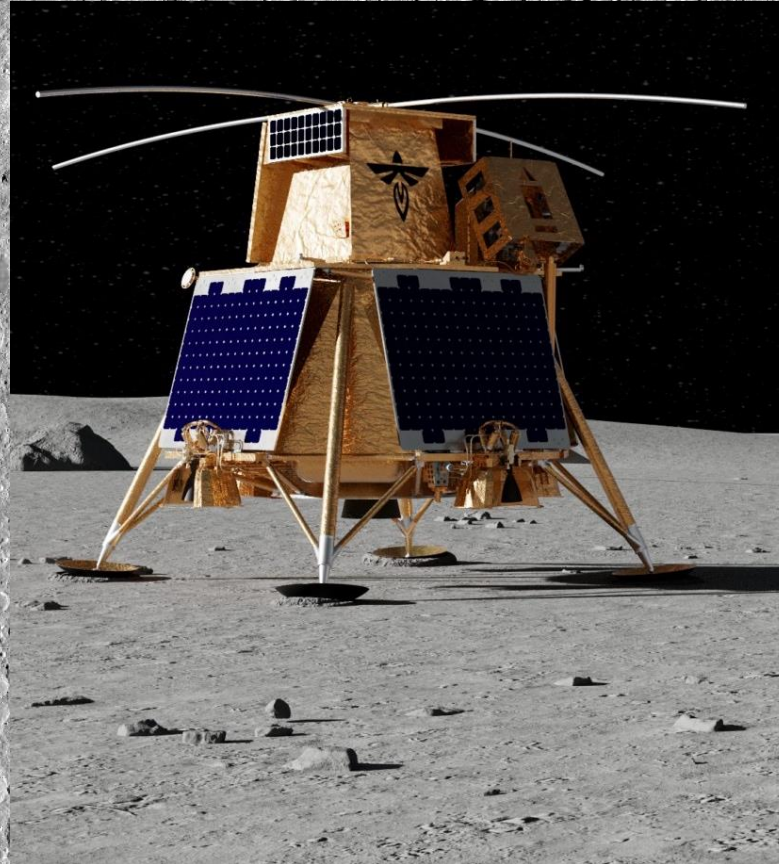


Radio Astronomy Payloads on NASA CLPS Missions

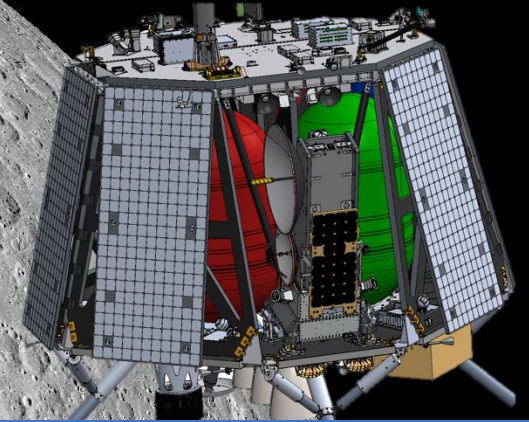
see Burns+ 2021, *Planetary Science Journal*, 2, 44B



Intuitive Machines delivered ROLSES (Radio wave Observations at the Lunar Surface of the Electron Sheath) to the lunar South Pole in February 2024.



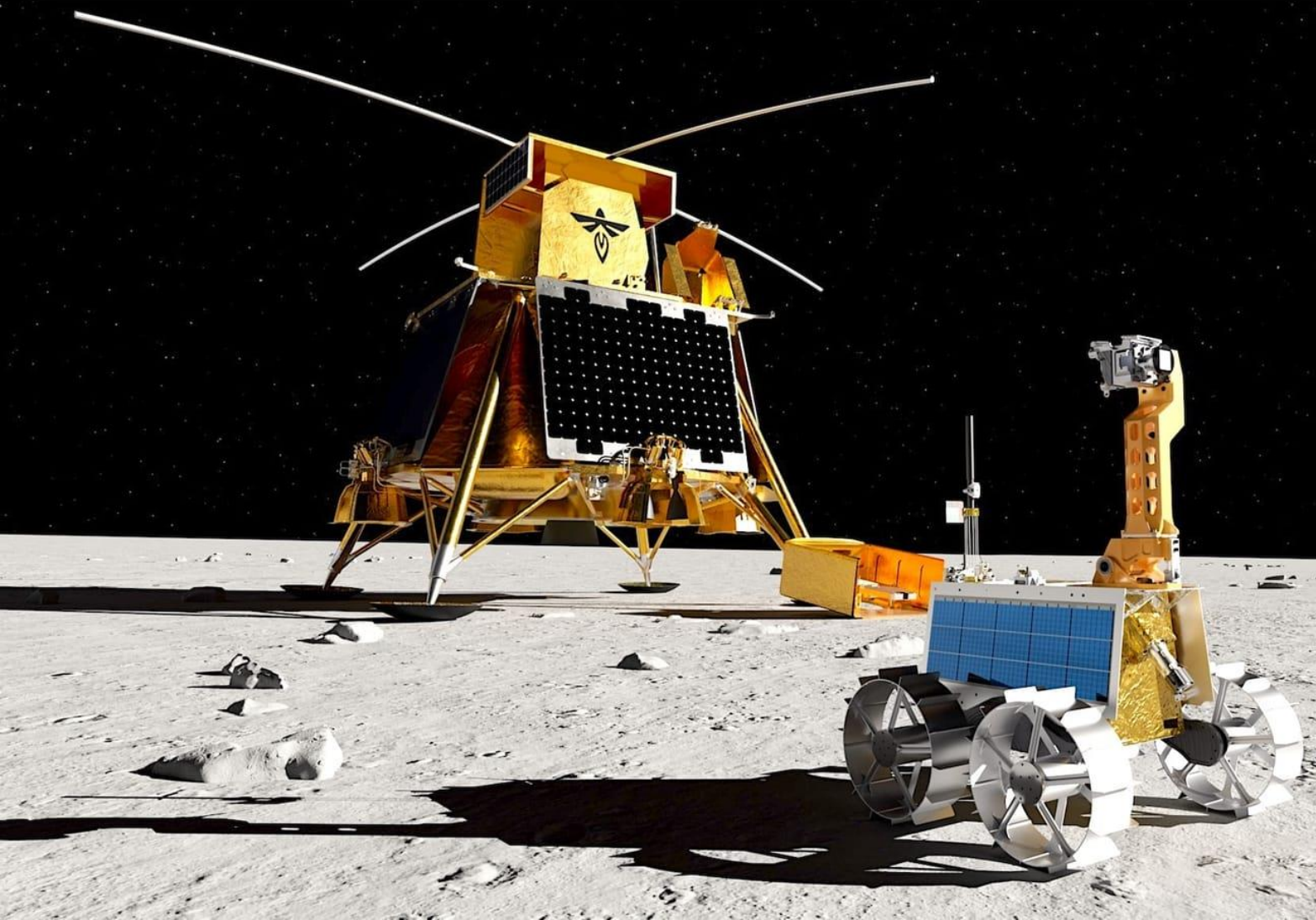
Firefly Aerospace will land LuSEE-Night on far side in Q1 2027. It probes the Dark Ages of early Universe.



LuSEE – Lite will land in the Schrödinger Impact Basin on far side late in the decade. Science includes measuring plasma waves & surface-geospace interactions.



ROLSSES-2 will be delivered to near-side Gruithuisen domes in ~2028 on Firefly Blue Ghost 3 lander.



Courtesy of Firefly Aerospace

Lunar Surface Electromagnetics Experiment at Night (LuSEE- Night)

The first 21-cm cosmology observations from the lunar far side at night

Collaboration between

- NASA: Stuart D. Bale (PI), UC-Berkeley
- DOE: Anže Slosar (Co-I), Brookhaven National Lab

LuSEE-Night is a pathfinder radio telescope on the lunar far side designed to explore a frequency range below 50 MHz that is inaccessible from the Earth. The instrument was constructed and is operated with funding from NASA and US Department of Energy. It will be delivered to the surface of the Moon as part of the NASA Commercial Lunar Payload Services (CLPS) mission CS-3 operated by Firefly Aerospace. Calibration signals will be provided by Firefly Aerospace as NASA CLPS mission CS-4.

Bale+, 2023, <https://arxiv.org/abs/2301.10345>



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 0.1-50 MHz 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.*



Assembly of Blue-Ghost 2 lander + orbiter at JPL prior to vibration testing

FARSIDE: Farside Array for Radio Science Investigations of the Dark ages and Exoplanets

Jack Burns and Gregg Hallinan

Co-PIs of FARSIDE

JPL Team

Issa Nesnas

Patrick McGarey

Adarsh Rajguru

Matthew Bezkrovny

Varhaz Jamnejad

Jim Lux

Eric Sunada

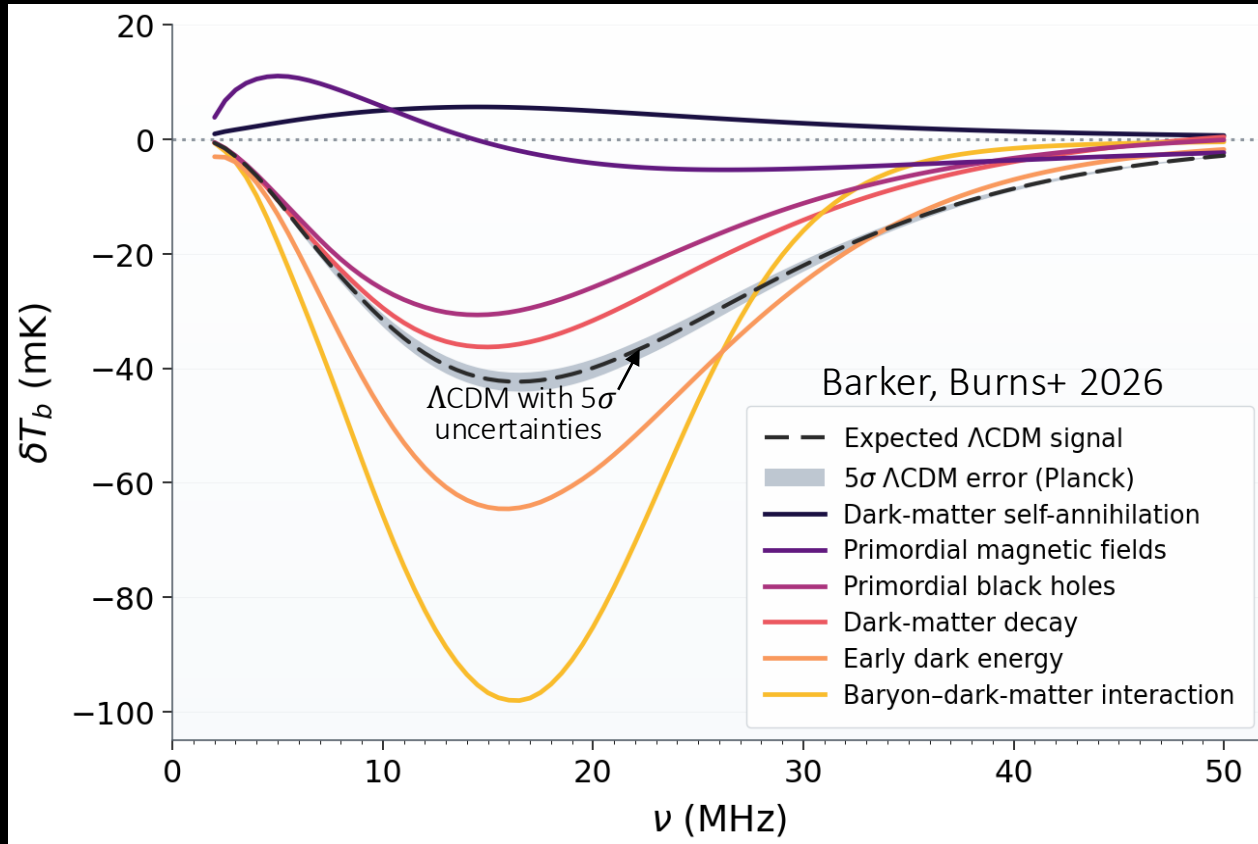
Co-I

Alex Hegedus (Space Science
Institute)



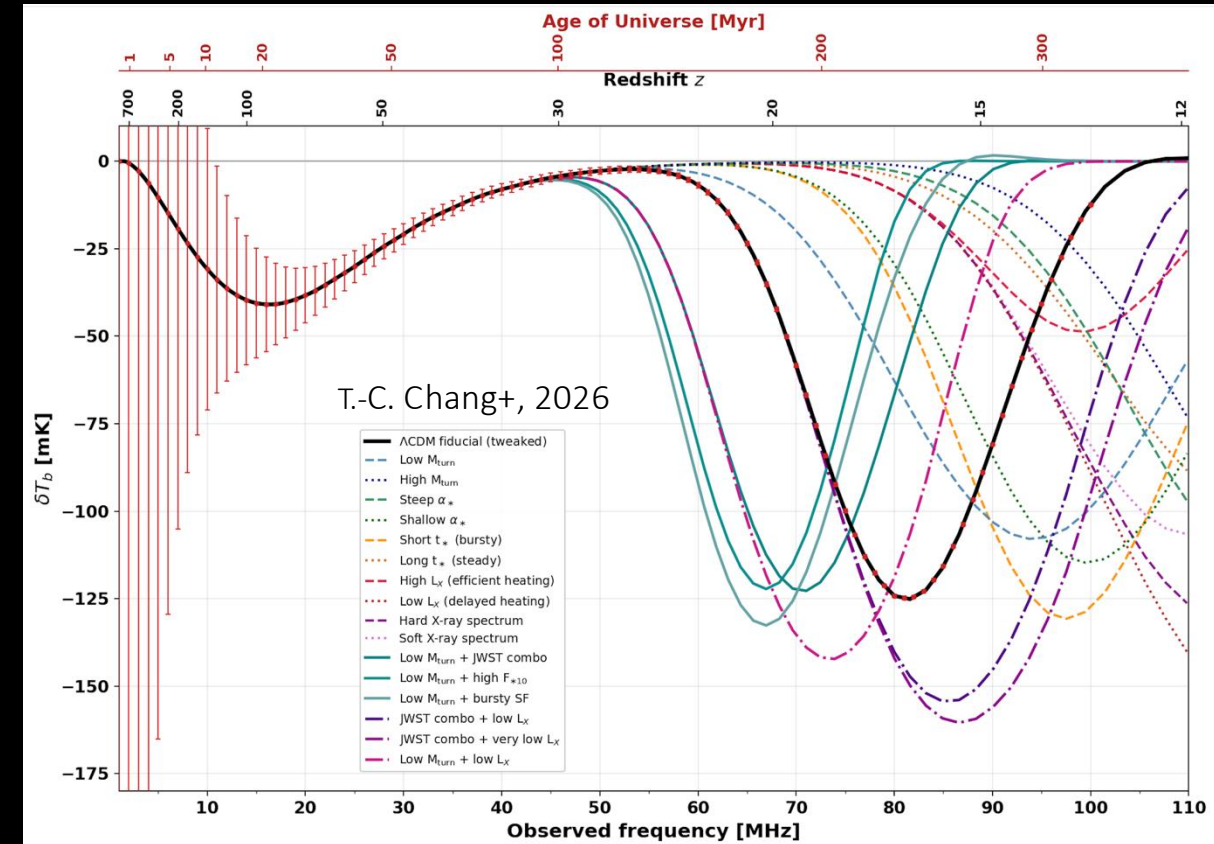
FARSide Sensitivity to Cosmology and Astrophysics

Dark Ages Exotic Physics



Any deviation from precise Λ CDM model is a detection of physics beyond the standard model.

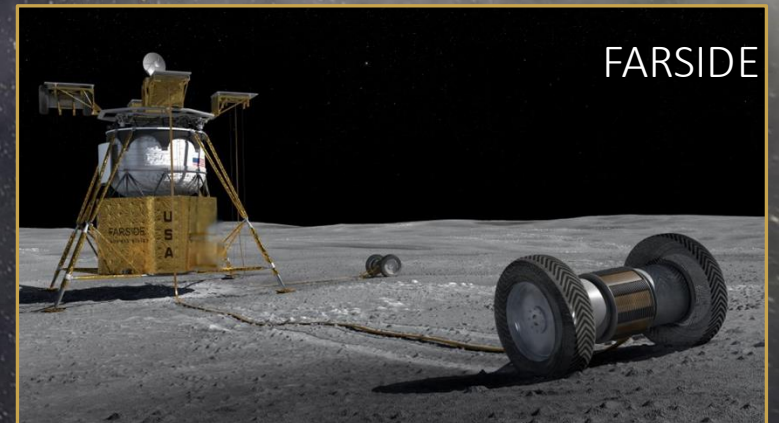
Cosmic Dawn Astrophysics & Star Formation



Shape and spectral turning points measure when first stars & black holes ignited, their mass, and stellar population.

Summary & Conclusions

- *The Dark Ages is where Physics Beyond the Standard Model likely will be revealed - dark matter interactions, early dark energy, inflationary non-Gaussianity.*
- *ROLSES & LuSEE-Night are reducing risk for low frequency arrays by measuring the effects of the lunar environment.*
- Initial radio arrays on the Moon, such as FARSIDE, could be the first to detect new physics & first constraints on Pop III stars.



Extra Slides

Exploring the Dark Ages Frequency Band with LuSEE-Night

- Telescope operates in 1-50 MHz band corresponding to $z = 27-1400$.
- Observes through lunar night using ~ 40 kg of rechargeable batteries. Total mass of LuSEE-Night = 102 kg.
- Lifetime on lunar surface up to 2 years.
- Firefly Blue Ghost-2 lander ceases operations on lunar surface after first lunar day giving LuSEE-Night full control over EMI environment.
- Antennas are 3-m stacers in cross-dipole configuration.
- Spectrometer is based upon Parker Solar Probe FIELDS instrument that makes voltage measurements.
- Far-field calibration source in lunar orbit to map radio beam. Turntable rotates antenna for 2-D mapping of beam.

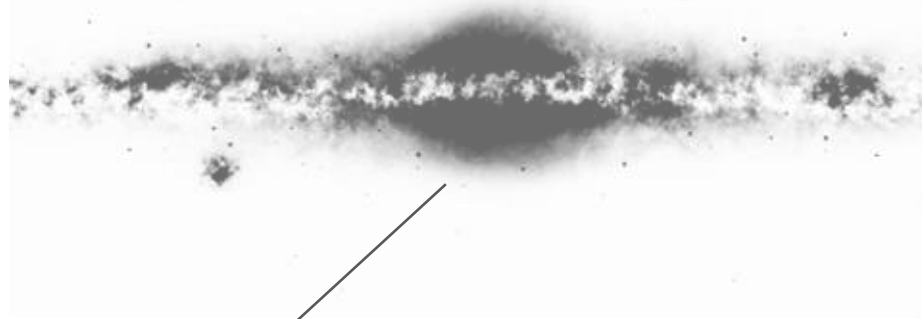
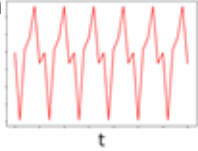


Assembly of Blue-Ghost 2 lander + orbiter at JPL prior to vibration testing.

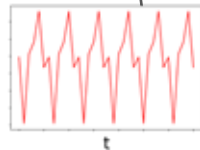
LuSEE-Night Far-Field Calibration



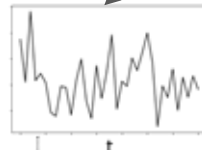
Calibration service beams a known waveform



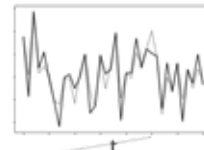
Instrument receives sum of sky signal (dominant) and calibration waveform



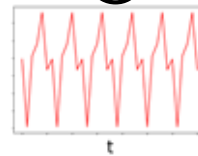
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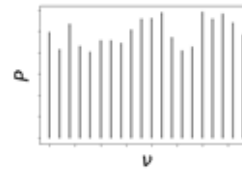
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*



A **copy** of template waveform is used to cross-correlate and isolate the subdominant calibration contribution.

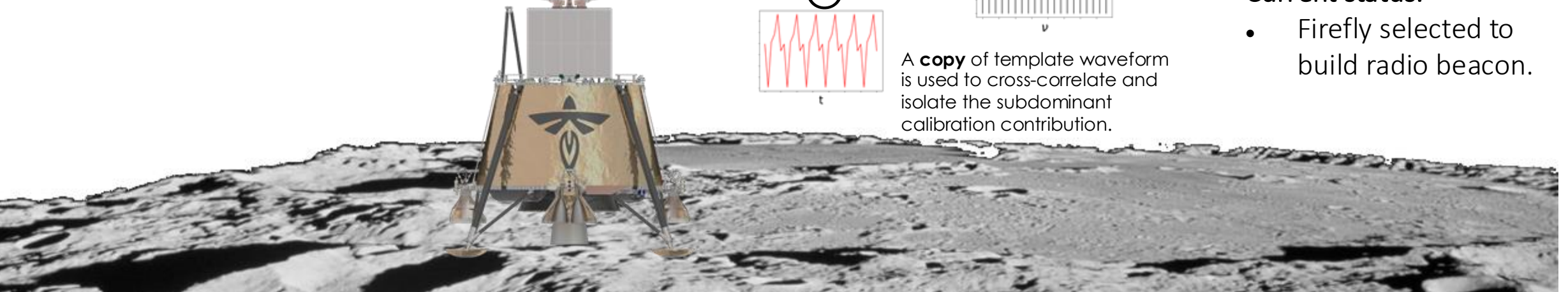


Advantages of cross-correlation technique:

- 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](https://arxiv.org/abs/2201.11806) for similar approach on the ground

Current status:

- Firefly selected to build radio beacon.



SunRISE – Technology Precursor for FARSIDE

PI: Susan Lepri, University of Michigan

Project Manager: Jim Lux, Caltech/JPL



SunRISE is an array of six CubeSats that will work together to study solar activity, observing low radio frequency emissions allowing us to better understand how the Sun is able to generate intense space weather storms

MoonRISE – Pathfinder for FARSIDE

PI: Saptarshi Bandyopadhyay, JPL/Caltech

Co-PIs: Marin Anderson, JPL/Caltech; Alex Hegedus, Space Sciences Institute

Radio Interferometer (RI)
(100 kHz to 30 MHz RF band)

9 Dipoles (3.5 m tip-to-tip length,
Dipole Electronics in 14.7 cm-dia. Puck)

Ground Penetrating Radar (GPR)
(300–2000 MHz RF band) on CLPS rover

CLPS Rover

Tether Deployment
System on CLPS rover

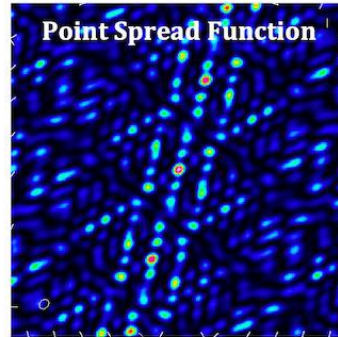
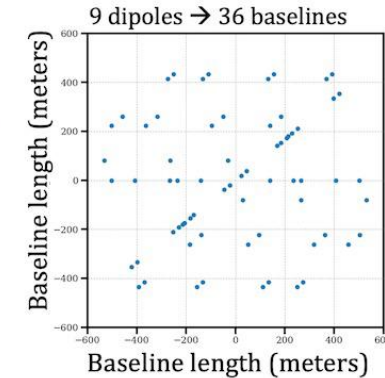
CLPS Lander

Lander Electronics Box,
includes Power-over-Fiber
Lasers and Data Acquisition
and Processing System

Tether (RF-data and Power over
Optical Fiber, 1.5 km length)

1 Cross-correlate
every antenna pair

2 Fourier
Transform



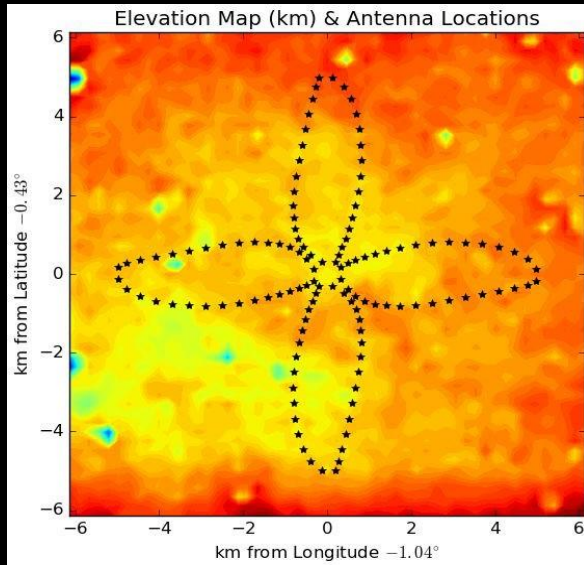
Milky Way
Galaxy

Uranus
Sun

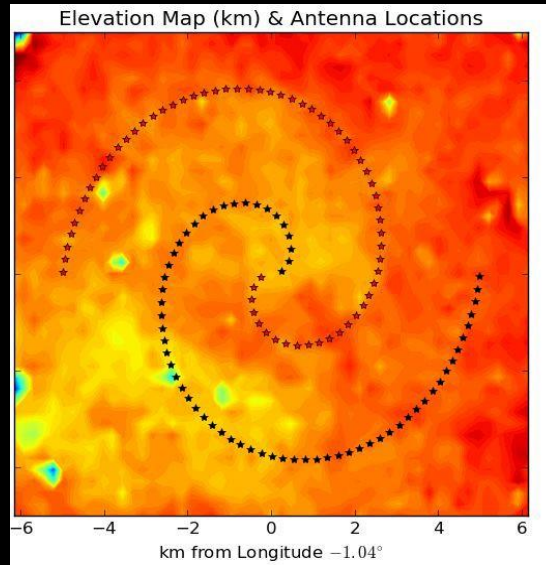
3 Image the
entire sky in
100 kHz –
30 MHz RF
band,
with 24 kHz
spectral and
0.1 sec time
resolution

Antenna Configuration

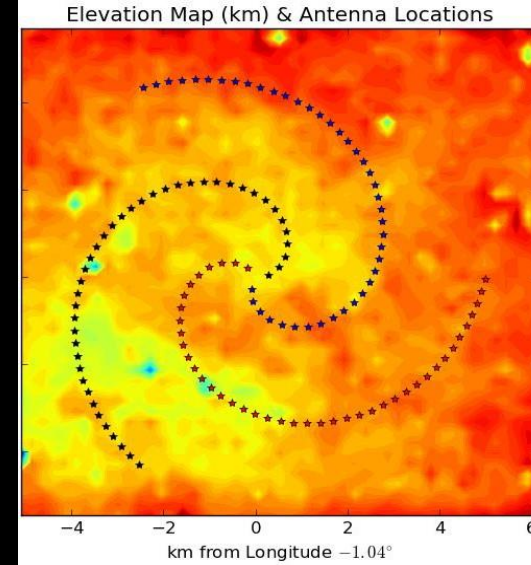
- 128 Dipole Antenna pairs



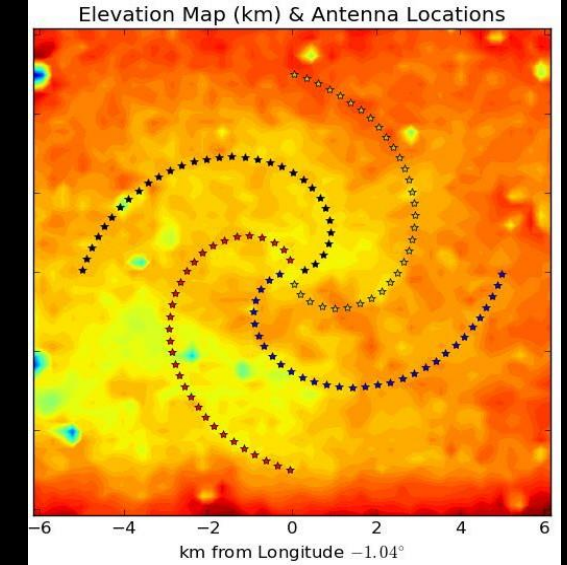
(a)
Original: Petal
48 km total
12 km/petal



(b)
2-arm Spiral
31 km total
15.5 km/arm



(c)
3-arm Spiral
33 km total
11 km/arm



(d)
4-Arm Spiral
36 km total
8.9 km/arm
Slightly better response
than (a), (b), and (c)