

FARVIEW

Lunar Farside Radio Array

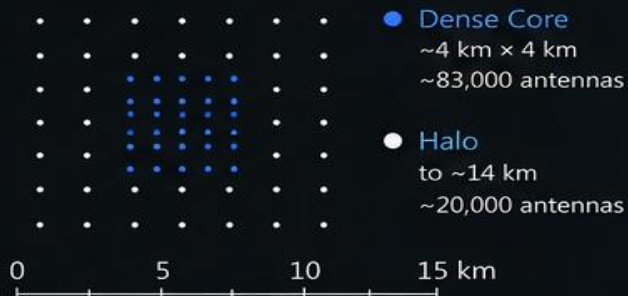
Probing the Dark Ages ($z \sim 30\text{--}100$),
exoplanets, and the low-frequency Universe
at 1–50 MHz

- ~100,000 crossed-dipole antennas
- Dense core (4 km) for large-scale modes
- Halo to ~14 km for resolution & calibration
- Deployed by autonomous lunar robots
- Located in the radio-quiet lunar farside

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ARRAY ARCHITECTURE



- Funded by NASA Innovative Advanced Concepts (NIAC), Phase I & II awards
- See Burns et al. 2026, arXiv2601.16170

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

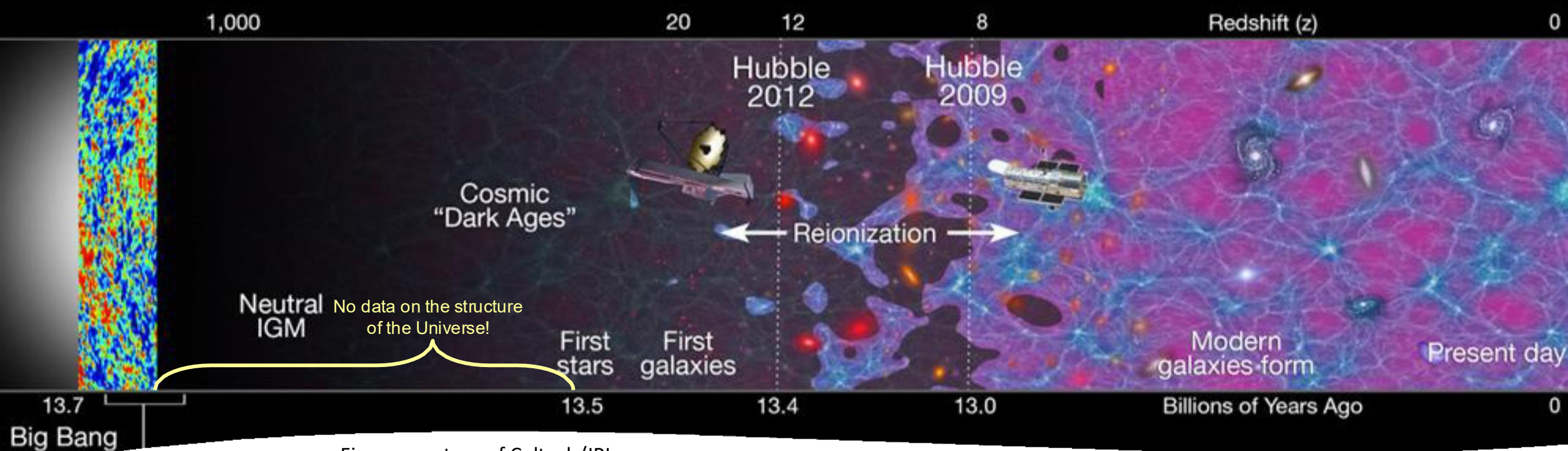
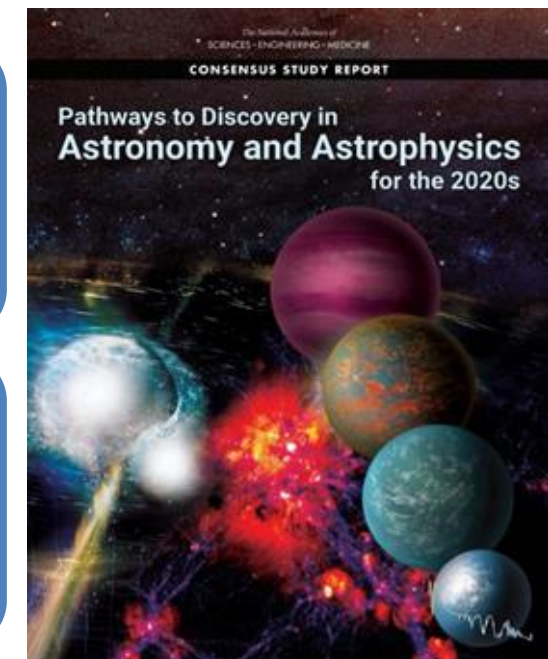


Figure courtesy of Caltech/JPL

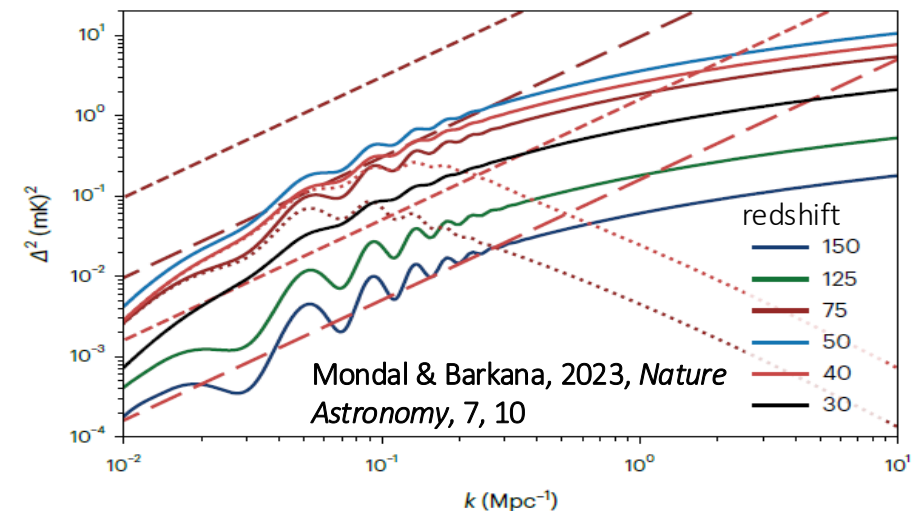
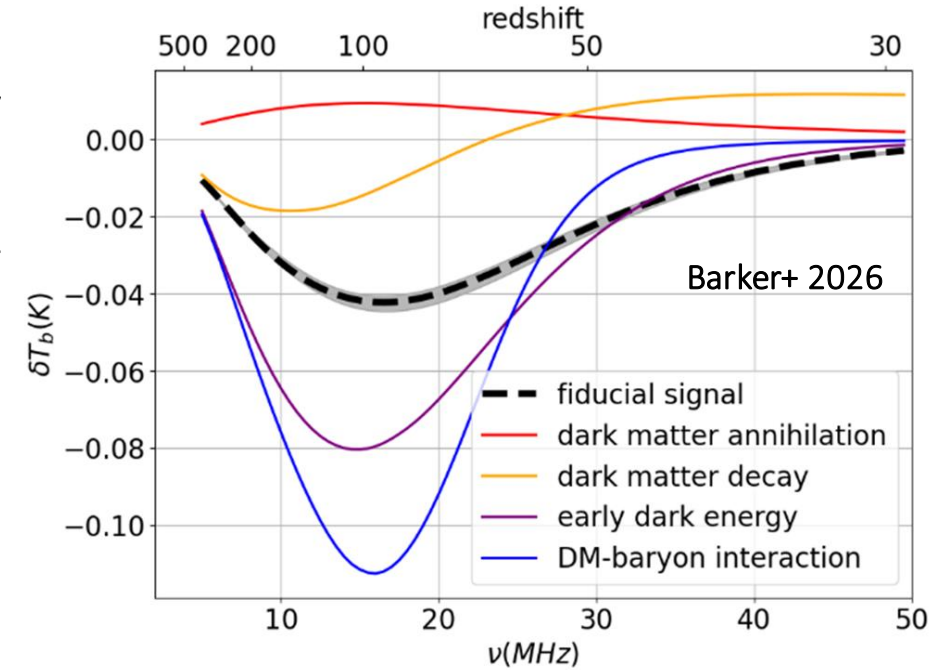
The Astro2020 Decadal Survey cosmology panel singled out the Dark Ages as the **priority Discovery Area in Cosmology**; and identified "needed capabilities to include... both higher sensitivity and a better understanding of instrumental systematics and astrophysical couplings."

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.

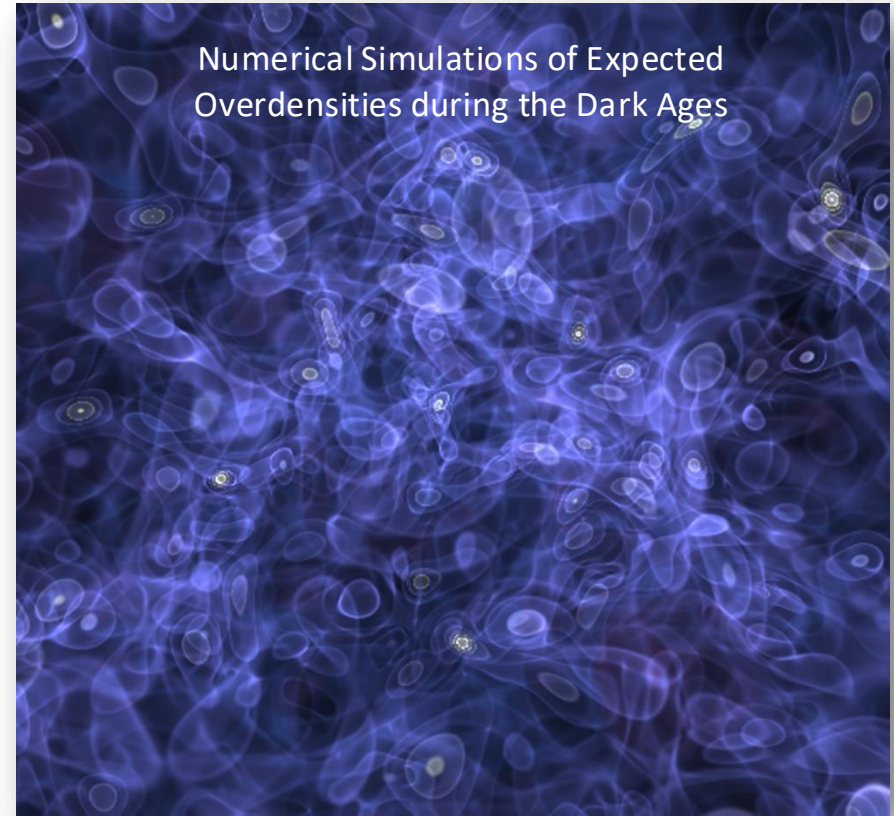
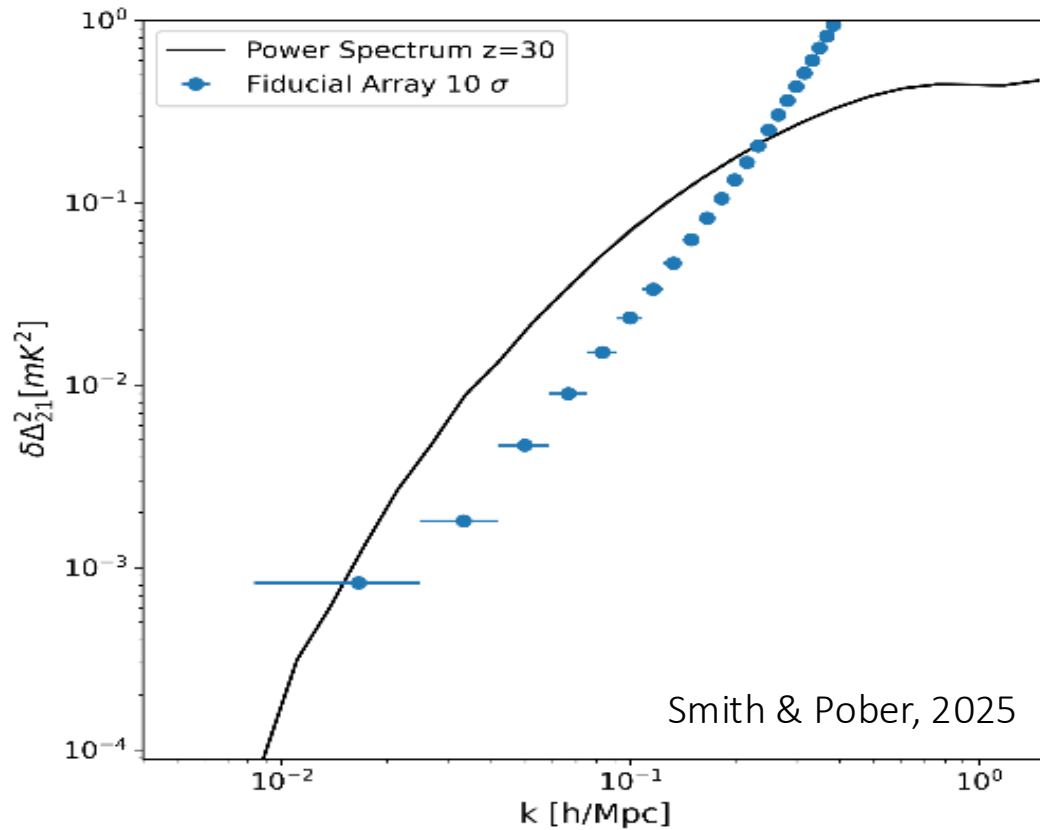


Exploring the Dark Ages of the Early Universe

- Global 21-cm spectrum can be measured by single or a few antennas in total power mode.
- Using an interferometer, structure power spectra & tomographic maps trace evolution of Universe from before/during birth of first stars.
- Departure from these well-constrained predictions will provide insights into new physics.
 - Probes a 3-D volume (thanks to redshift information)
 - No Silk damping: can (in principle) probe all the way to the Jeans length ← small scales are where non-standard physics may show up!
 - Structure formation still in linear regime: straightforward to interpret without messy galaxy physics
 - All told, over 10^6 times more modes than CMB!



Simulations of Sensitivities with Beamforming



Credit: N. Musoke *et al.*, Phys. Rev. Lett. (2020)

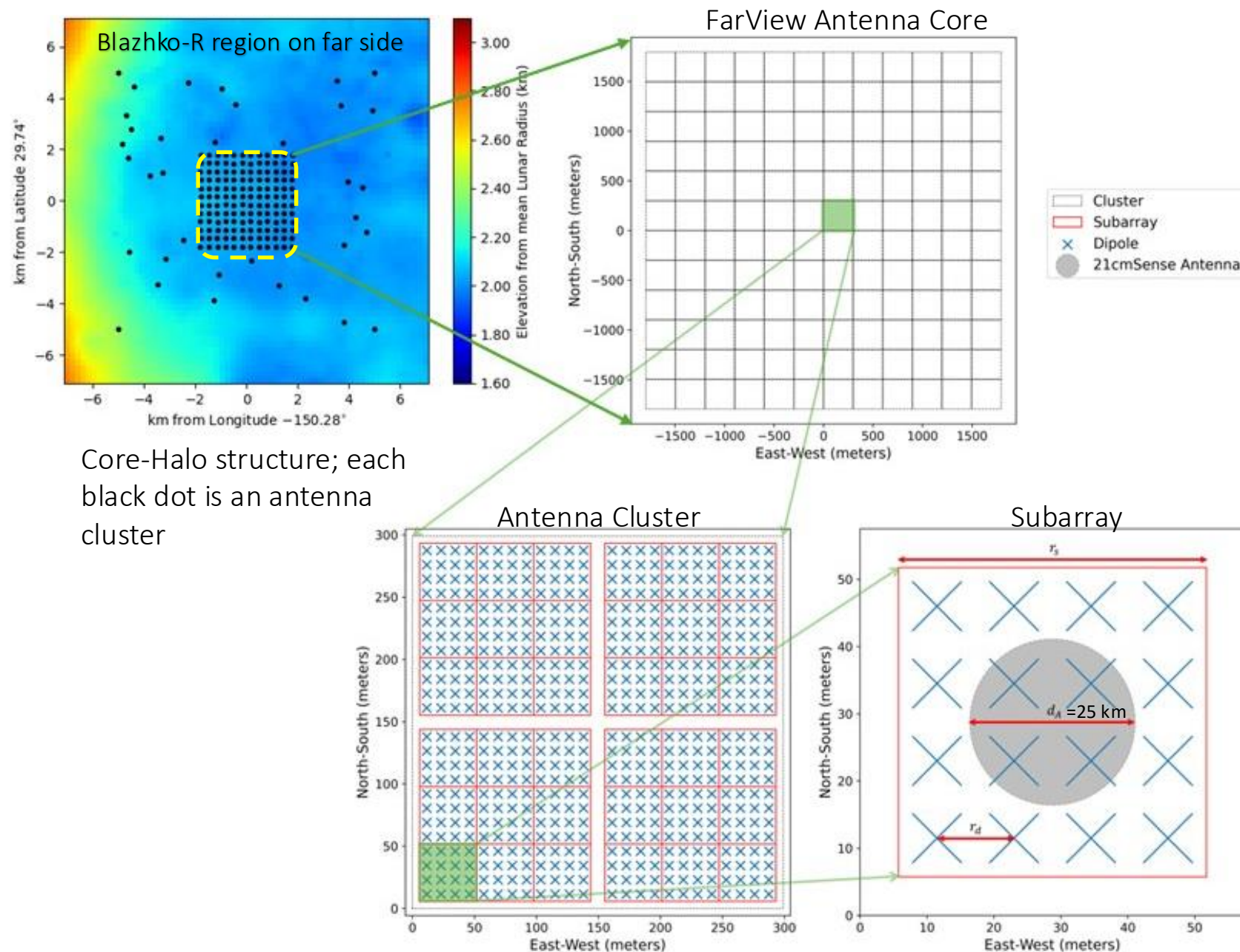
Numerical simulations using *21cmSense* code reveals that

- Sensitivity is set almost entirely by **thermal (sky) noise**, not sample variance — so the key design lever is the number of **small baselines** => **Need 80,000 antennas packed into 4x4 km core.**
- An FFT-based **EPIC** beamformer minimizes both data volume and on-site compute relative to traditional cross-correlation.

FarView Architecture

Use interferometry to gain access to wide range of scales

- Cosmological signal is strongest on large spatial scales (access with dense core)
- Foregrounds need to be modeled with high precision (use outrigger antennas, 14×14 km halo)
- Close packed 4×4 km array core (~80,000 dual-polarization dipole antennas) has the sensitivity to achieve a $> 10\sigma$ detection of the 21 cm signal with 5 years of operation (50% duty cycle)
- 19 high potential lunar sites identified for FarView.
- Science begins after the first subarray and cluster are deployed!





FAR VIEW OF THE MOON

Critical & Enabling Technologies

- Critical Gaps

- Demonstrate Molten Regolith Electrolysis (MRE) on the Moon to extract metals and manufacture antennas and solar panels.
- Deploy 100,000 antennas using autonomous rovers and A.I.

- Design Drivers

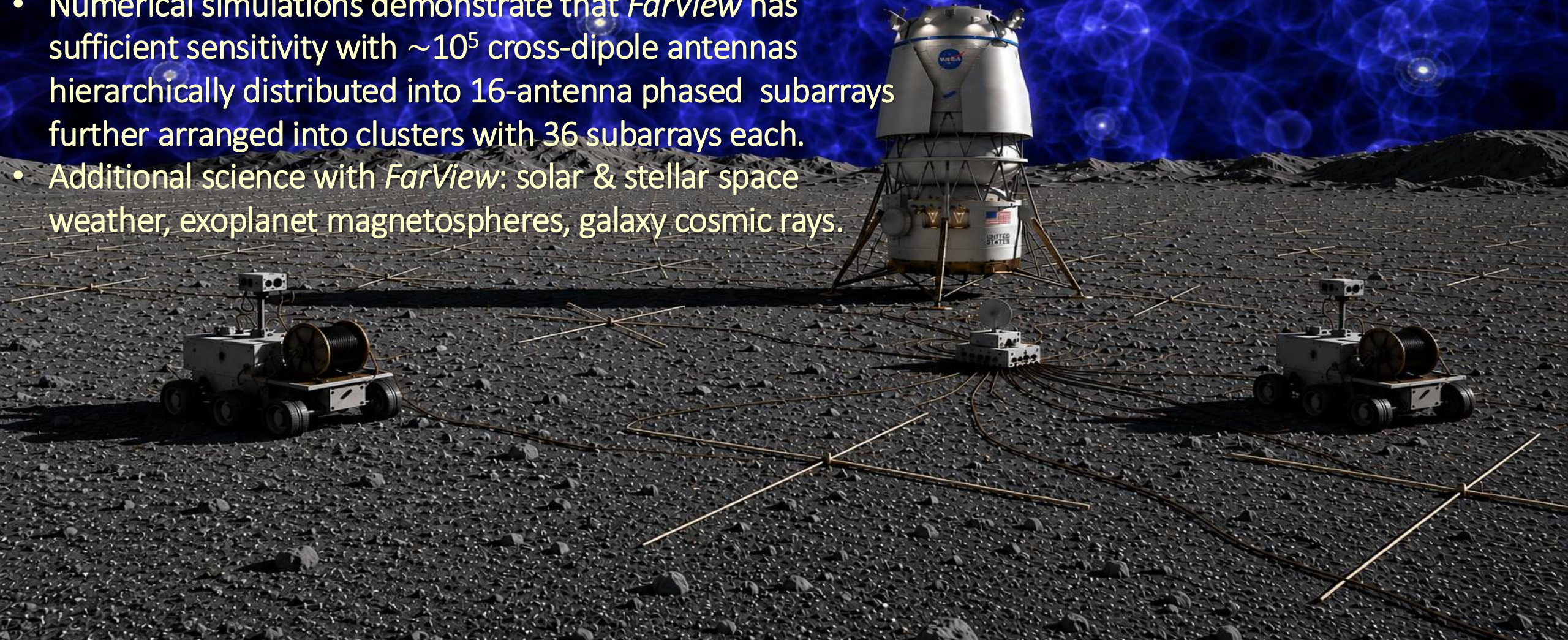
- Deliver rovers & MRE reactors using high mass capacity landers (Starship and/or Blue Moon Mk-2)
- Low radio noise environment requires lunar far side.

- Leveraging External Capabilities

- Utilize Artemis transportation, comms, and infrastructure on the Moon.
- Commercial landers
- Commercial partners with ISRU in-situ manufacturing.

Summary & Conclusions

- *FarView* will measure 3-D spatial/spectral fluctuations to explore new physics potentially including dark matter, neutrinos, & inflation.
- Numerical simulations demonstrate that *FarView* has sufficient sensitivity with $\sim 10^5$ cross-dipole antennas hierarchically distributed into 16-antenna phased subarrays further arranged into clusters with 36 subarrays each.
- Additional science with *FarView*: solar & stellar space weather, exoplanet magnetospheres, galaxy cosmic rays.



Estimated Data Rates for FarView



FarView will generate prodigious amounts of data. To estimate the data rates, we assume:

- 100,000 cross-dipoles within subarrays with bandwidth of 5-50 MHz.
- 5 kHz spectral resolution with $\sim 9,000$ spectral channels over 45 MHz bandwidth.
- Core is 4 km & halo is 14 km in diameter. Resolutions at 45 MHz for core is $\sim 5.7'$ and for halo is $1.7'$.
- Beamforming of subarrays reduces down correlations from 10^{10} to N_{stations}^2 .
 - N_{stations} for core = $144 * 36 = 5184$
 - N_{stations} for halo = $35 * 36 = 1260$
- Integrate for ~ 1 min & 2.4 mins for longest and shortest baselines, leading to 1440 and 600 integrations every 24 hrs.
- Assume 64 bits to store complex visibilities.

With all these parameters, the data rate per day to be downlinked to Earth is:

- Data-rate/24^h (halo) = $N_{\text{stations}}(N_{\text{stations}}-1)/2 * N_{\text{channels}} * N_{\text{bits}} * N_{\text{pol}} * N_{\text{integrations}}$
= $793,170 * 9000 * 64 * 4 * 1440$
= 329 TB/day
- Data-rate/24^h (core) = $1,342,433 * 9,000 * 64 * 4 * 600$
= 232 TB/day

We are exploring methods to reduce data rate including:

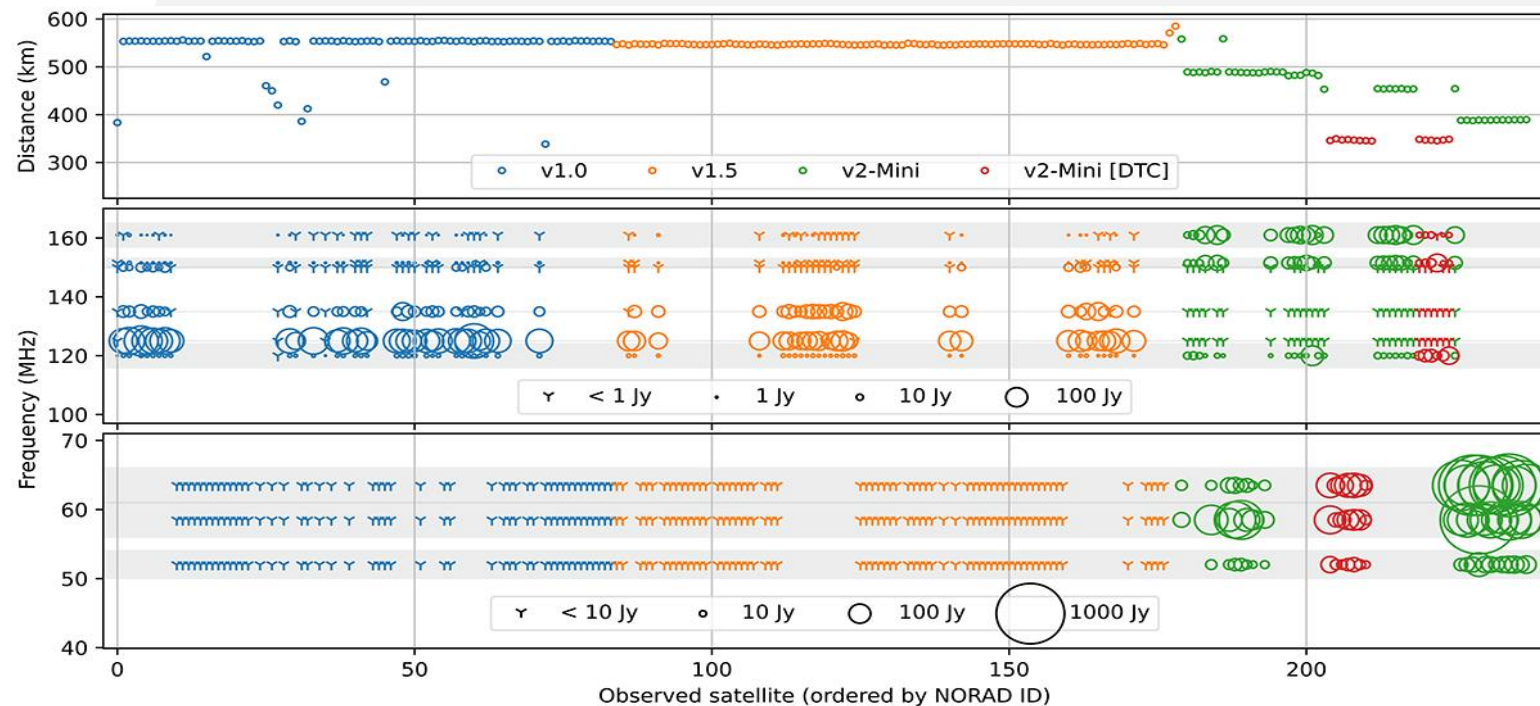
- Aggressive baseline-dependent averaging / fringe-rate filtering.
- Real-time averaging of redundant visibilities.
- **EPIC** (E-Field Parallel Imaging Correlator). Reduces # of computations from N^2 to $N * \log(N)$.

FarView Mission Design Parameters Derived from the Science Analyses				
Parameter		Value		Rationale
Location		Radio-quiet zone on the lunar far side		The radio quiet zone is a $\sim 65^\circ$ radius circular area centered on 0° latitude, 180° longitude) on the lunar far side where the natural and anthropogenic low frequency radio signals from the Earth (a major noise source for FarView) are almost totally blocked. This very low noise environment is required to detect the Cosmic Dark Ages signal.
Frequency Band		5 - 50 MHz		For detection of highly redshifted 21-cm radiation from the Cosmic Dark Ages.
Total Number of Dipoles		100,000		Minimum necessary to achieve cosmology sensitivity requirement.
Antenna Distribution		Core/Halo distribution		Core should have $\sim 80\%$ of total number of antennas. This distribution is required to supply sensitivity in the core to detect the Dark Ages signal and enough sensitivity in the halo to adequately remove the foreground.
Antenna Length		~ 10 meters		Optimal length to produced required sensitivity.
Antenna Separation		11.5 meters		Optimized separation that maximizes sensitivity and is viable given the antenna length and rover maneuverability.
Antenna Distribution		Zig-Zag Pattern		Cross-dipole antennas are required to measure polarization. Non-cospatial cross dipoles can be achieved by deploying dipoles with one orthogonal to the next in a zig-zag pattern.
Positional Tolerance for Placement of Individual Antennas		~ 2 meters in all three axes		Tolerance needs to be $< 0.1\lambda$ at 15 MHz and flexibility to avoid small boulders & craters.
Orientation Tolerance for Placement of Individual Antennas		≈ 10 degrees		Maintain coherence for polarization with post-processing corrections.
Polarization Measurement		Equal number of antennas for both orientations		Allows calculation for full Stokes parameters enabling polarization measurements.
Lunar Surface		Relatively smooth and flat with undulations of < 2 m in height		Tolerance needs to be $< 0.1\lambda$ at 15 MHz over the area spanned by 3 dipole antennas.
Lunar Subsurface		High crustal thickness (≥ 25 km)		Minimize subsurface reflections of the incoming radio signal that will distort the radio beam.
Visible Horizon		Avoid sites with nearby mountains		A jagged horizon, one with lots of mountains, will compromise the data analysis. Map of horizon will be needed for data analysis to remove horizon effects.

Radio Leakage from Starlink Satellites – Implications for the Moon

“Observations with the LOFAR radio telescope between 10 to 88 MHz and 110 to 188 MHz show broadband emission [from Starlink satellites]...The spectral power flux density of this broadband UEMR varies from satellite to satellite, with values ranging from 15 to 1300 Jy, between 56 and 66 MHz,” Bassa et al. 2024, A&A, 689, L10.

See also Krolkowski & Elvis, 2024, *Phil. Trans. Roy. Soc.*, in press.



Distances and power flux density measurements of Starlink satellites that passed through the beam pattern of the two 1 h LOFAR observations.