Science Cases for a Lunar Far Side Radio Array

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Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers: Panel on Heliophysics, Physics, and Physical Science Meeting No. 2

BROWN

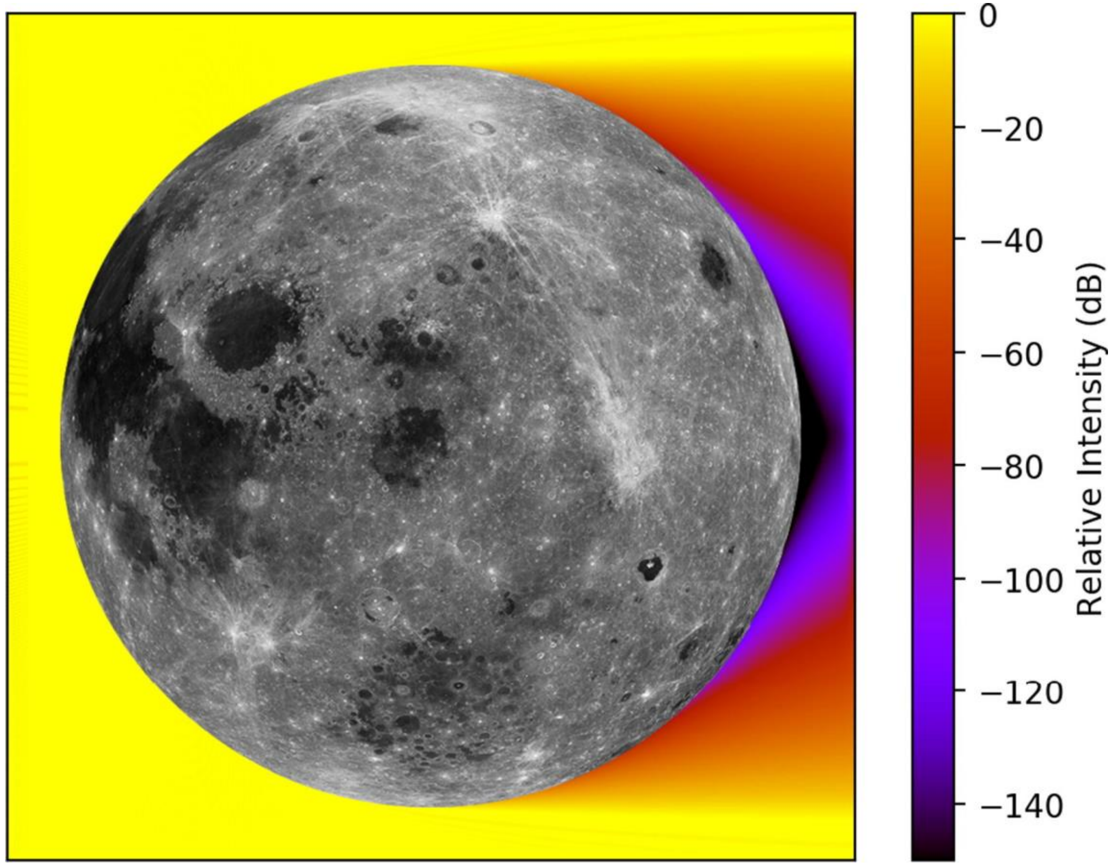
Outline

- The lunar far side
- Exoplanetary magnetospheres
- The dark ages 21 cm signal

The Lunar Far Side

Science for the lunar far side is driven by its unique combination of two key attributes

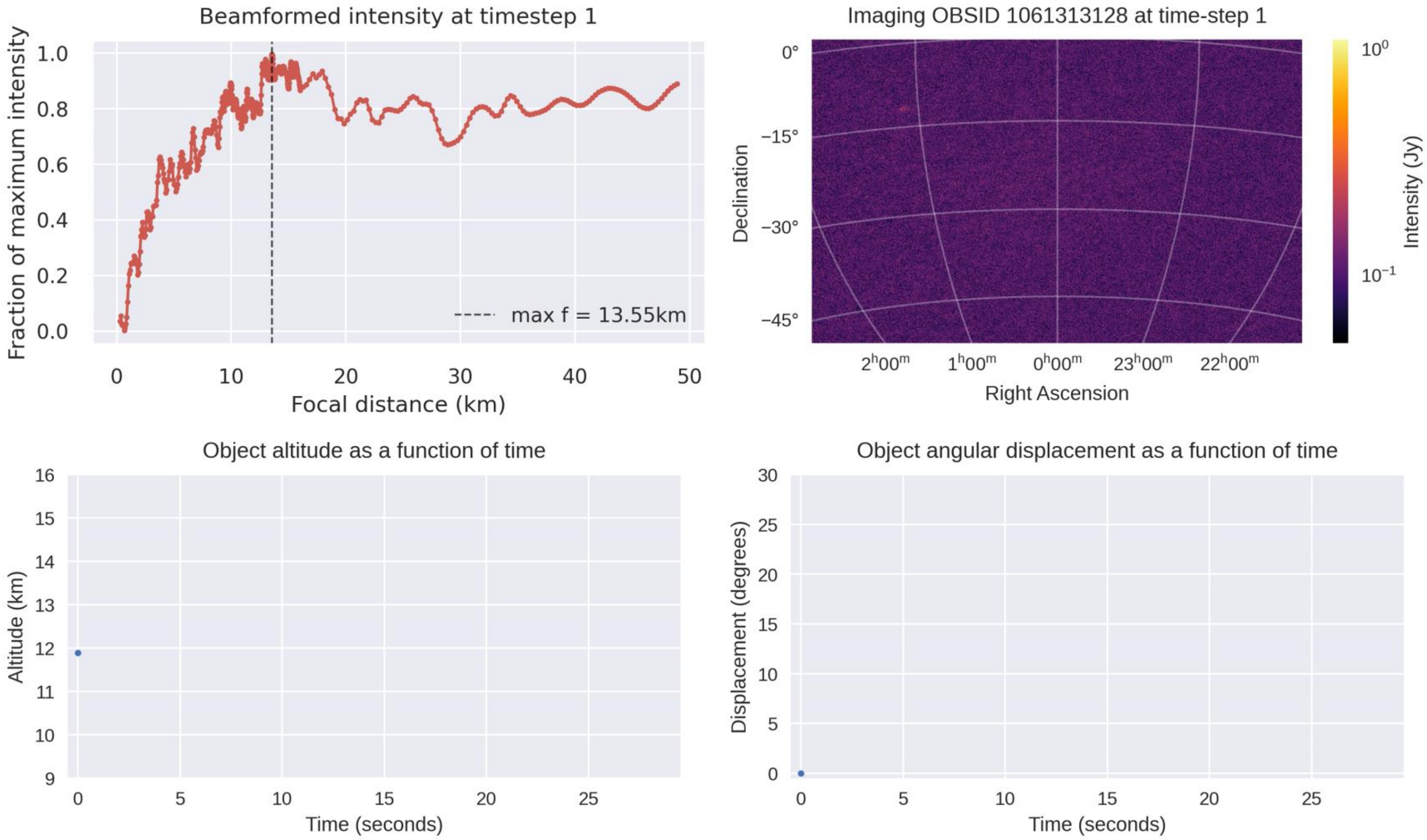
- Minimal ionosphere allows **access to low radio frequencies** (< 30 MHz)
- Minimal radio interference (particularly at mid-latitudes) allows both **long integrations** and **easier identification of transient phenomena**



Bassett et al. (2020)

RFI on Earth

- Look at data Murchison Widefield Array (MWA) at *Inyarrimanha Ilgari Bundara,* the CSIRO Murchison Radio-astronomy Observatory
  - Future site of SKA-Low and nominally the best place on Earth for low-frequency radio astronomy
- Near field interferometry techniques can be used to localize RFI sources in 3D
- This object is at 11.7 km altitude and moving at 792 km/hr
  - It's a commercial airliner!



Ducharme & Pober 2025

RFI on Earth

- Recent MWA data appears 100% contaminated by RFI, largely due to satellite constellations
- First generation Starlink had unintentional emission from a faulty power supply (di Vruno et al. 2023, Grigg et al. 2023)
- After fixes for second generation, satellites now appear 32 times brighter! (Bassa et al. 2024)
- There may not be any useable new data for 21 cm cosmology unless we can excise these sources in post-processing

Exoplanetary magnetospheres

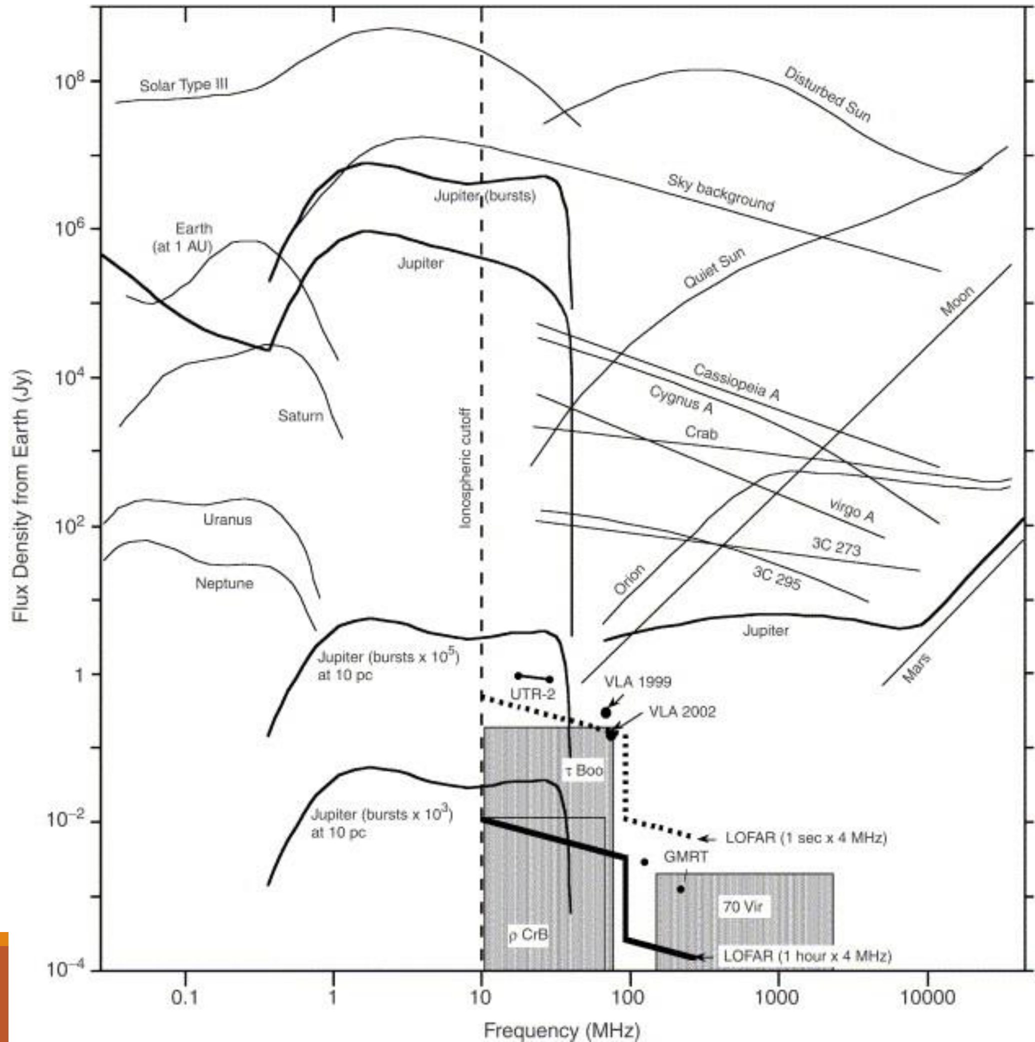
Impact and Limitations

Credit: Chuck Carter and Caltech/KISS

Exoplanetary magnetospheres

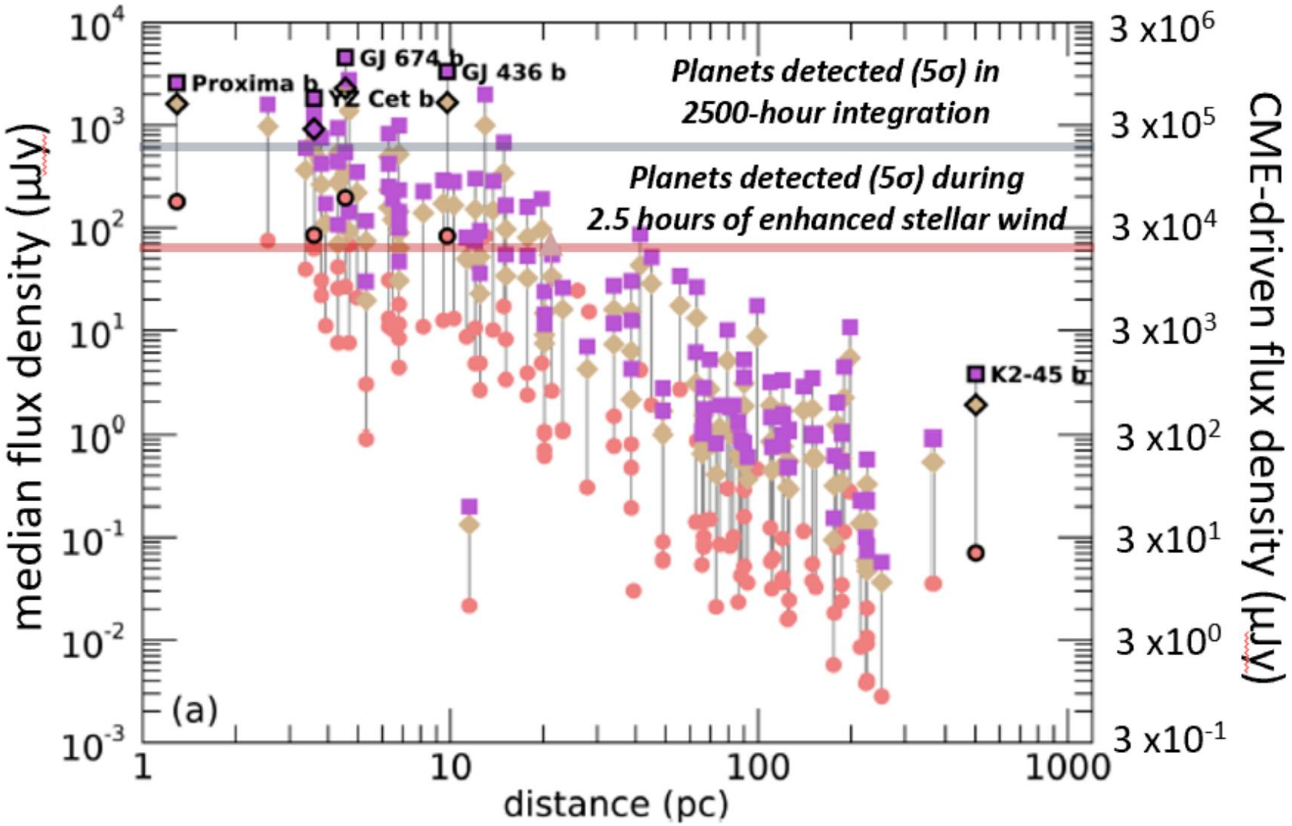
Zarka (2007)

- Many "habitable zone" exoplanets are around active M dwarf stars
  - Magnetospheres likely necessary to protect life from stellar radiation
- Radio signal strength and frequency cutoff depends on planet's field strength and size
- Earth-analog planets likely need observations < 1 - 10 MHz
  - Must take place above Earth's ionosphere



Detecting exoplanetary signals

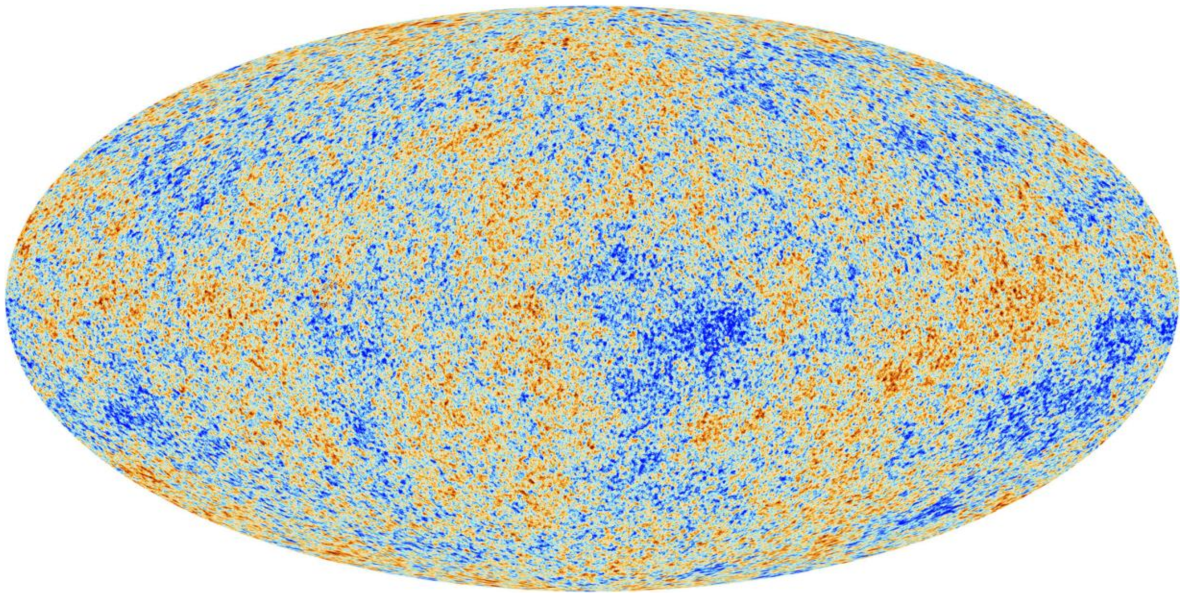
- Forecasts for FARSIDE show that 128 dipole antennas spread over ~10 km can detect a population of Earth / super-Earth sized planets with magnetospheres
- Circular polarization can distinguish planetary auroral emission from stellar radio emission
  - RFI exhibits complicated polarization properties, lunar far side location highly beneficial



Burns et al. (2019)

The dark ages 21 cm signal

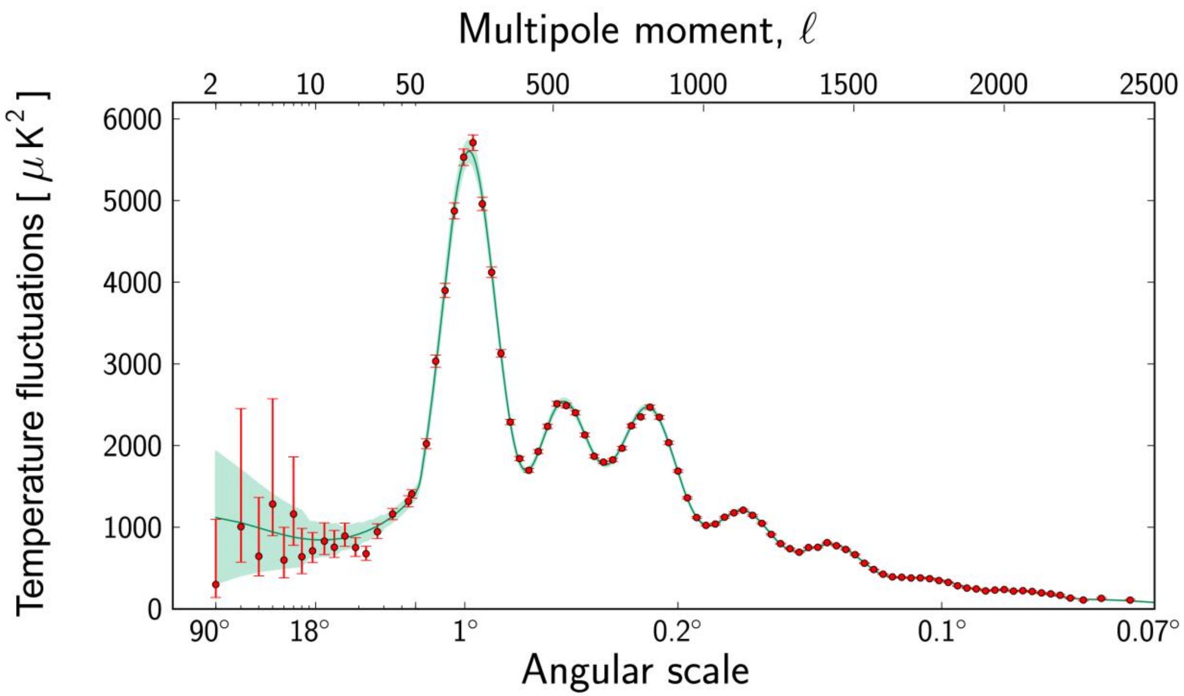
The CMB



Credit: Planck Collaboration

- The CMB is the most important source of information about the cosmology of our Universe
- Probes the Universe 380,000 years after the Big Bang
- Small fluctuations in temperature trace the **density perturbations** that seed all future structure

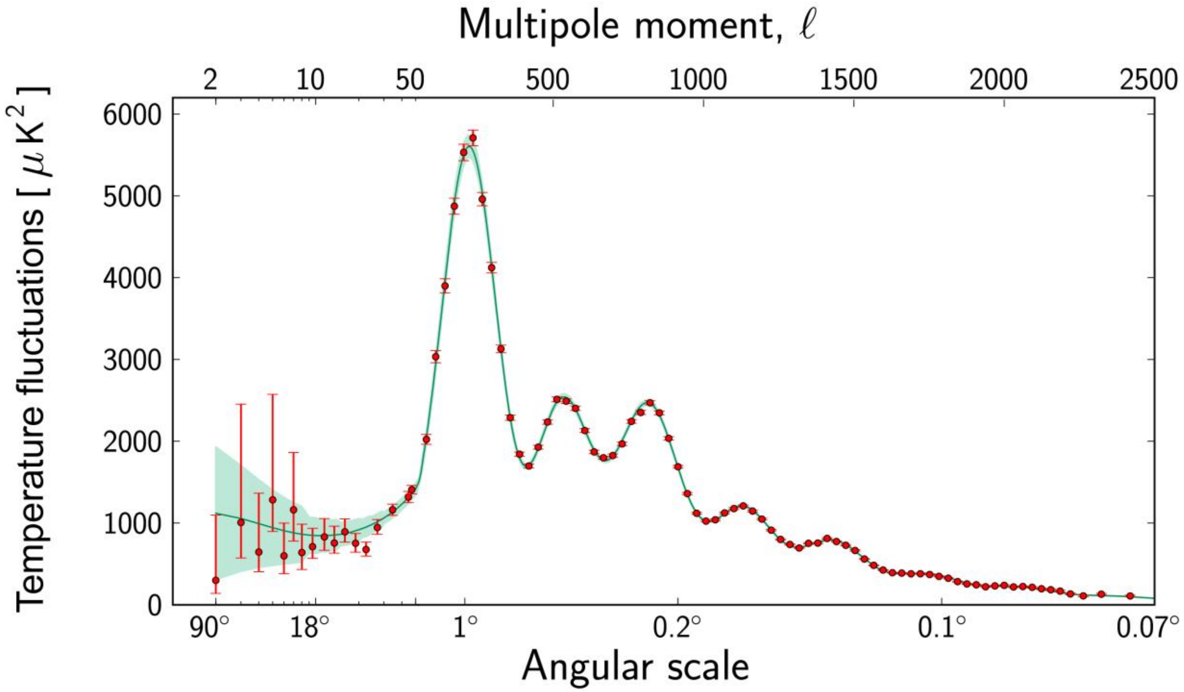
Why is the CMB so valuable?



Credit: Planck Collaboration

- The power spectrum of cosmic density fluctuations is a prediction that follows from inflation
- Can fit power spectrum of CMB anisotropies with just 6 parameters: (1) baryon density, (2) dark matter density, (3) age of the universe, (4) amplitude, (5) spectral index, (6) reionization optical depth
- Processes leading from inflationary spectrum to CMB spectrum are *linear* and well-understood
- A tremendous amount of information still to be gleaned from secondary anisotropies and polarization

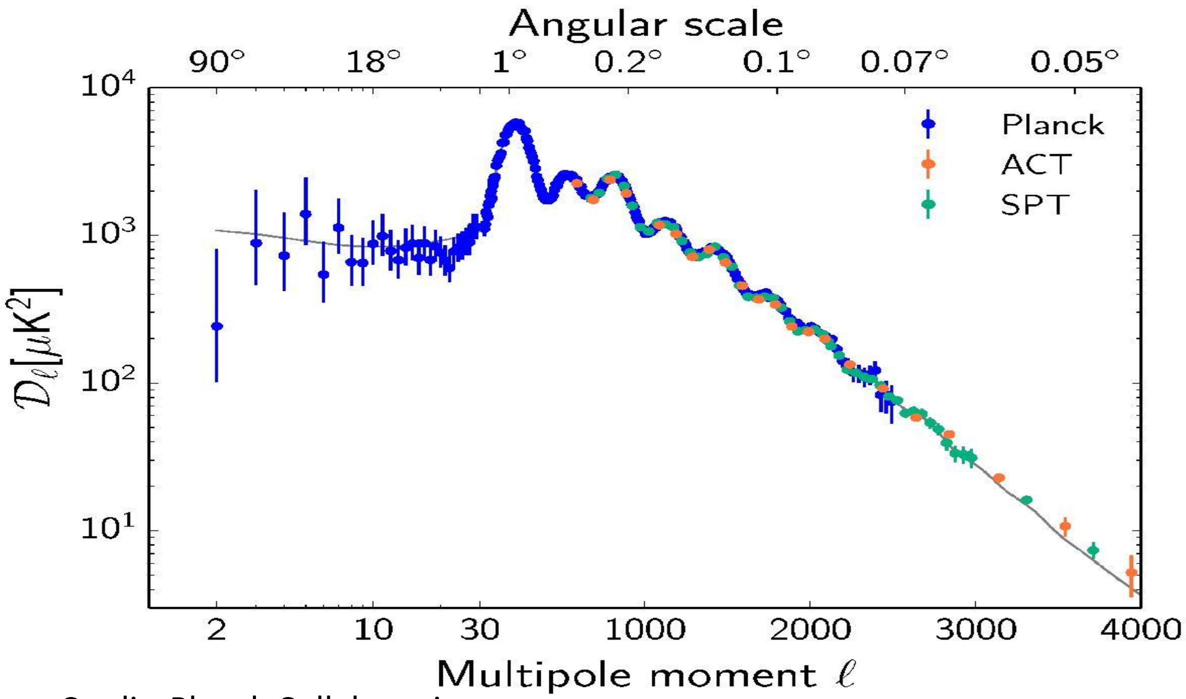
Limitations of the CMB: Large Scales



Credit: Planck Collaboration

- Measurements of the largest angular scales are fundamentally limited: "cosmic variance"
- Lowest multipoles are inconsistent with standard model at the edge of statistical significance (~2.5σ)
  - Could be evidence of new physics, but no way to confirm with CMB alone

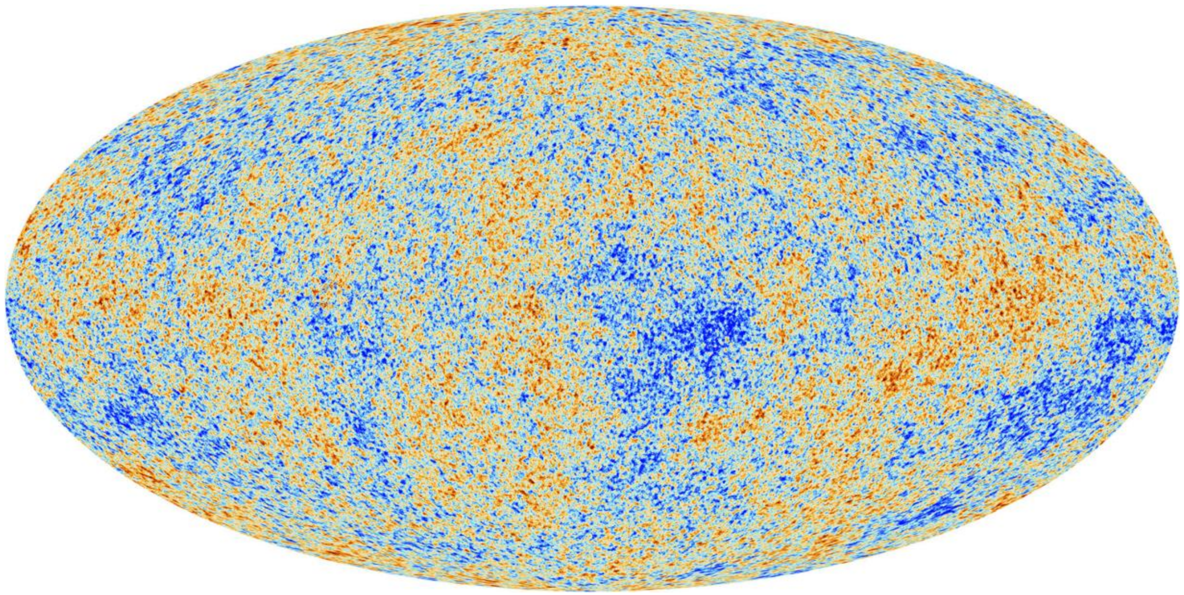
Limitations of the CMB: Small Scales



Credit: Planck Collaboration

- Small scales in the CMB are exponentially damped due to photon diffusion (Silk damping)
- Small scales of the density power spectrum can constrain running of the spectral index, curvature, neutrino masses, dark matter (among others!)
- Damping effect is specific to photons and, hence, the CMB — need other probes of cosmic structure to see what is happening at very small scales

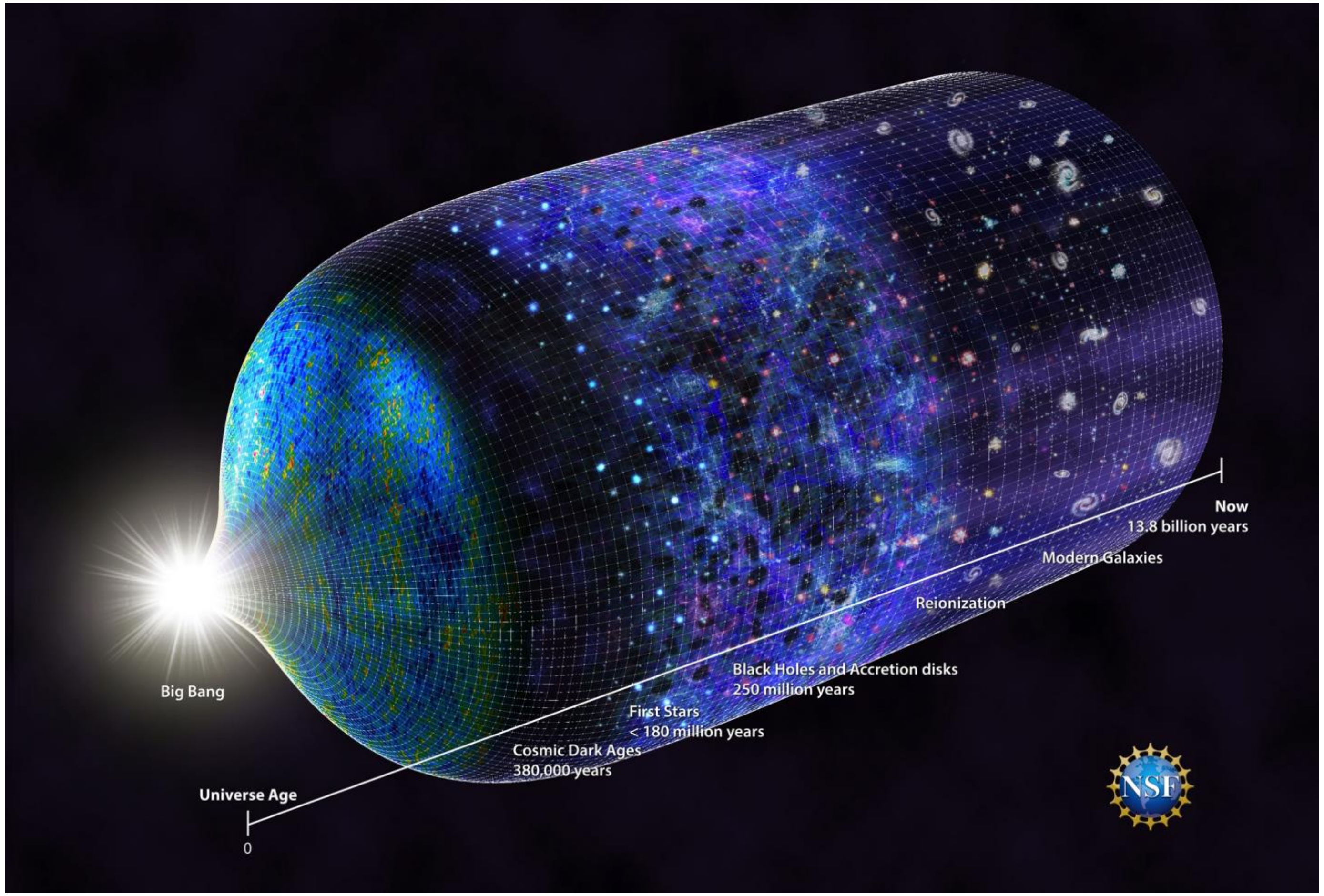
Limitations of the CMB: Total # of Modes



Credit: Planck Collaboration

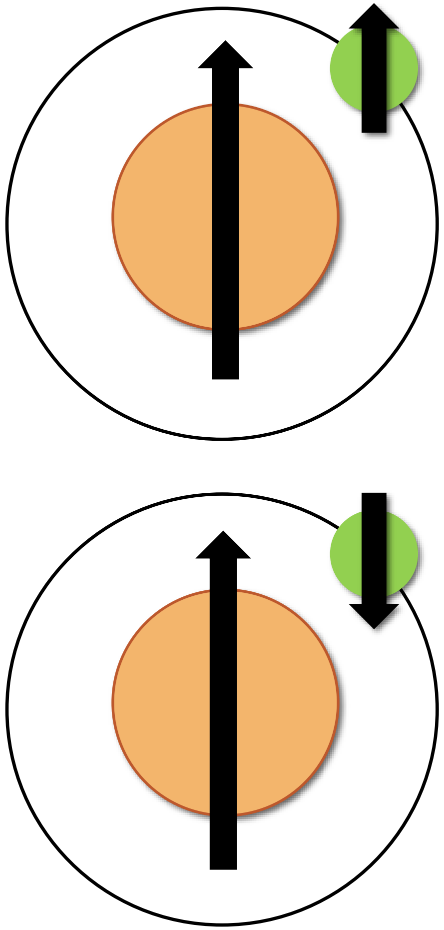
- Fundamentally, the CMB is **a surface**: can only fit in a specific number of modes (especially given lack of small scale information)
- Limits significance of key cosmological observables like non-Gaussianity
- To get more modes: measure **a volume**!

The Dark Ages



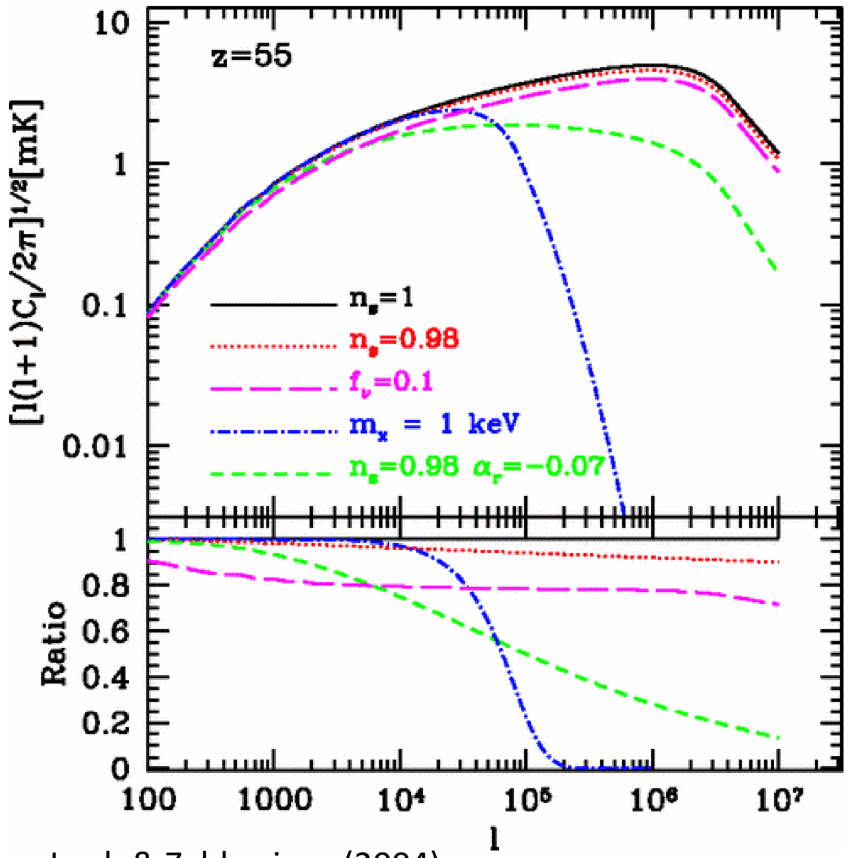
- Period of cosmic history **between** the formation of the CMB and the formation of the first stars
- Universe consists of dark matter, hydrogen & helium with slowly growing density perturbations
- No sources of electromagnetic radiation (other than already present CMB photons), except…

21 cm Hyperfine Signal From Hydrogen



- The most abundant element in the universe
  - 75% of all baryons by mass
- Hyperfine splitting energy differential of 5.9×10^{-6} eV
  - $\nu = 1420$ MHz
  - $\lambda = 21$ cm
  - T = 0.068 K → CMB is hot enough such that there are always atoms in the excited state
- Spectral line: observed redshift maps to cosmological distance

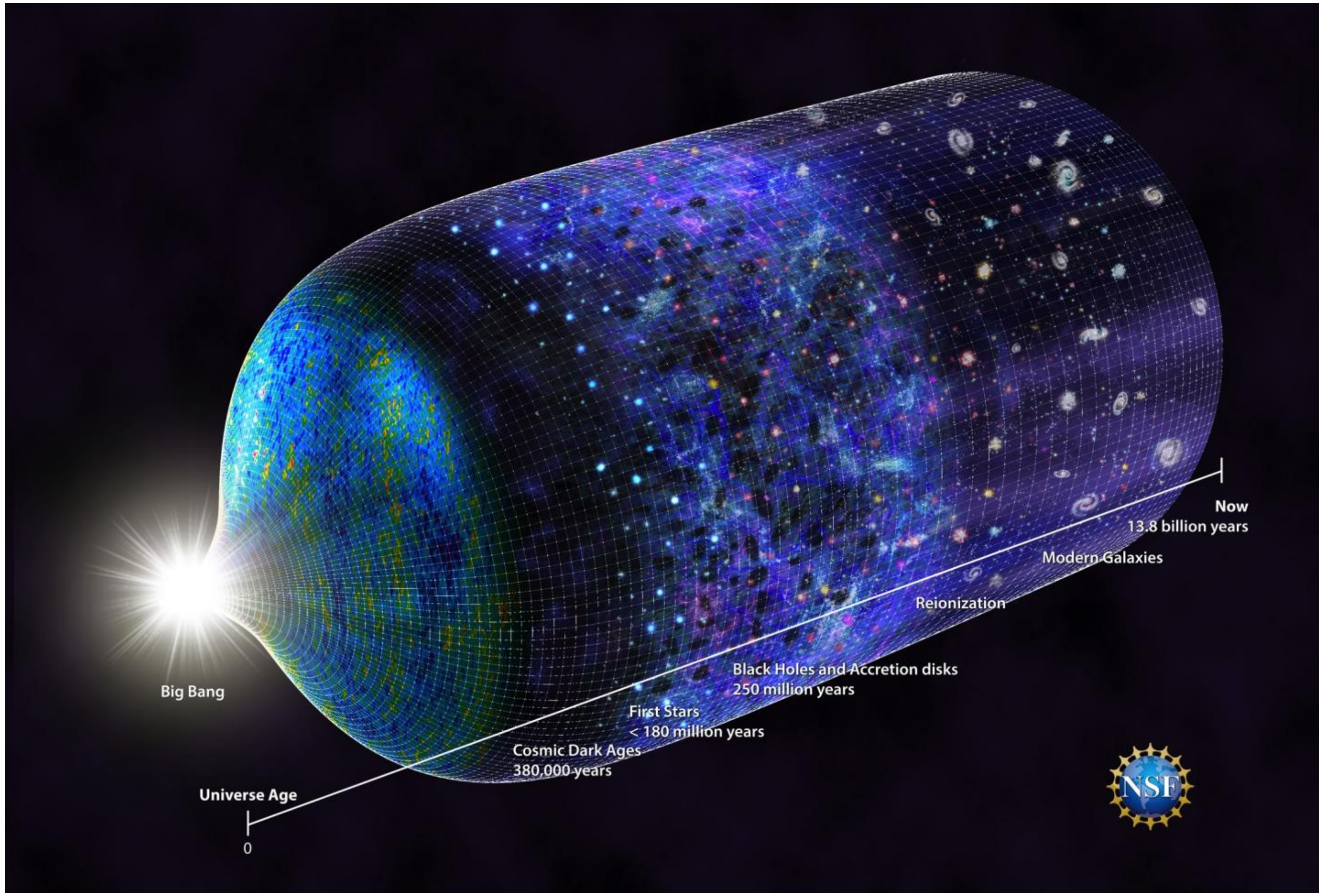
21 cm Dark Ages Observations



Loeb & Zaldarriaga (2004)

- Probes a volume (thanks to redshift information)
- No Silk damping: can (in principle) probe all the way to the Jeans length
- Structure formation still in linear regime: straightforward to interpret without messy galaxy physics
- All told, over 10^6 times more modes than CMB!
- The "discovery area" for cosmology this decade!

The Dark Ages vs. EoR



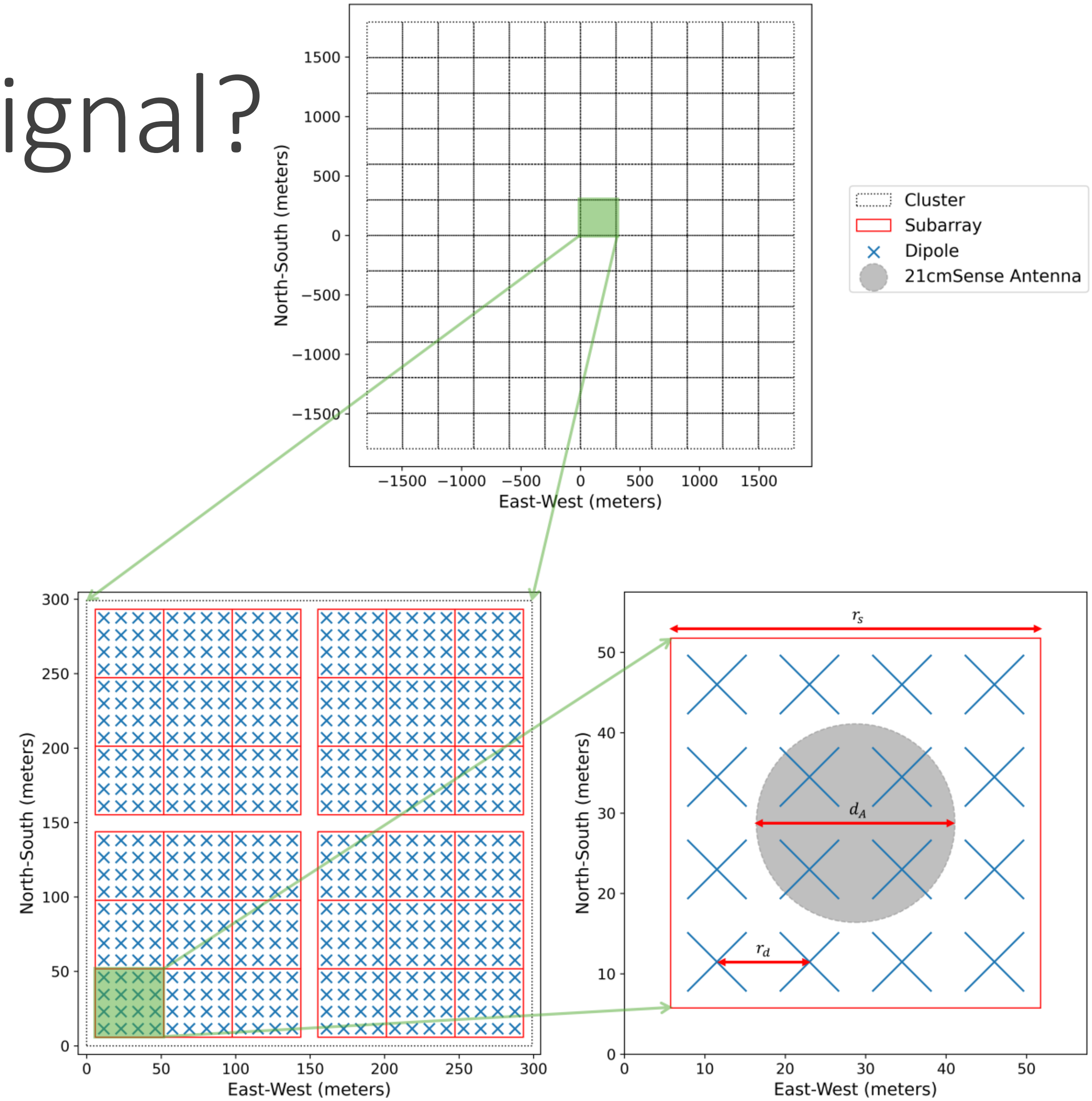
- The Epoch of Reionization (EoR) can also be studied through its 21 cm signal
  - Probes epoch of first stars and galaxies — a bridge between fundamental physics and astrophysics
- Signals come from a later period of cosmic history and hence are redshifted less
  - Meter wavelength emission can (in principle) be detected through the Earth's ionosphere
  - Experiments are *ground based*
- The EoR is interesting and exciting but probes inherently different physics
  - Only the dark ages signal provides a clean probe of fundamental physics

Can we detect the signal?

- Dark ages signal is fainter and noise is higher compared with EoR signal targeted by ground-based experiments

- 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 for high resolution)

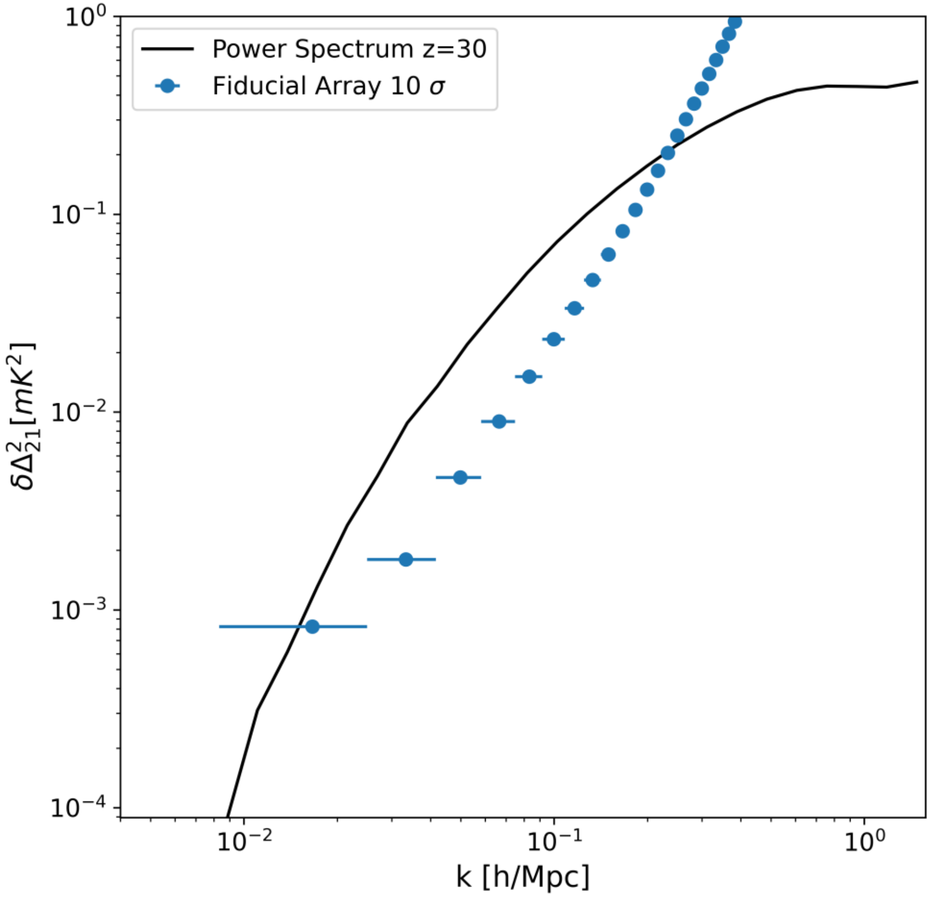
- A close packed 2.5 km^2 array core has the sensitivity to achieve a > 10σ detection of the z = 30 21 cm signal with 5 years of operation (50% duty cycle)



Smith & Pober (2025)

Can we detect the signal?

- Necessitates foreground subtraction that has not been required for ground-based experiments!
- Cosmological forecasting necessary to determine scientific impact of this scale of measurement



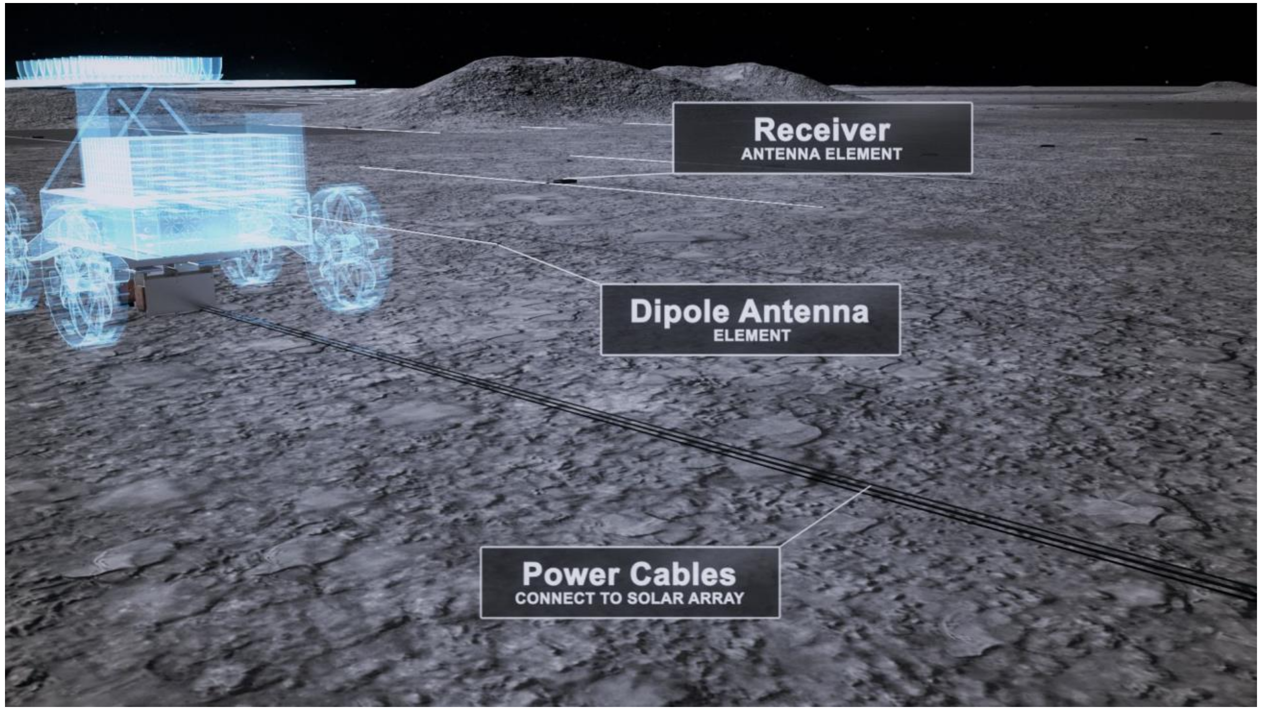
Smith & Pober (2025)

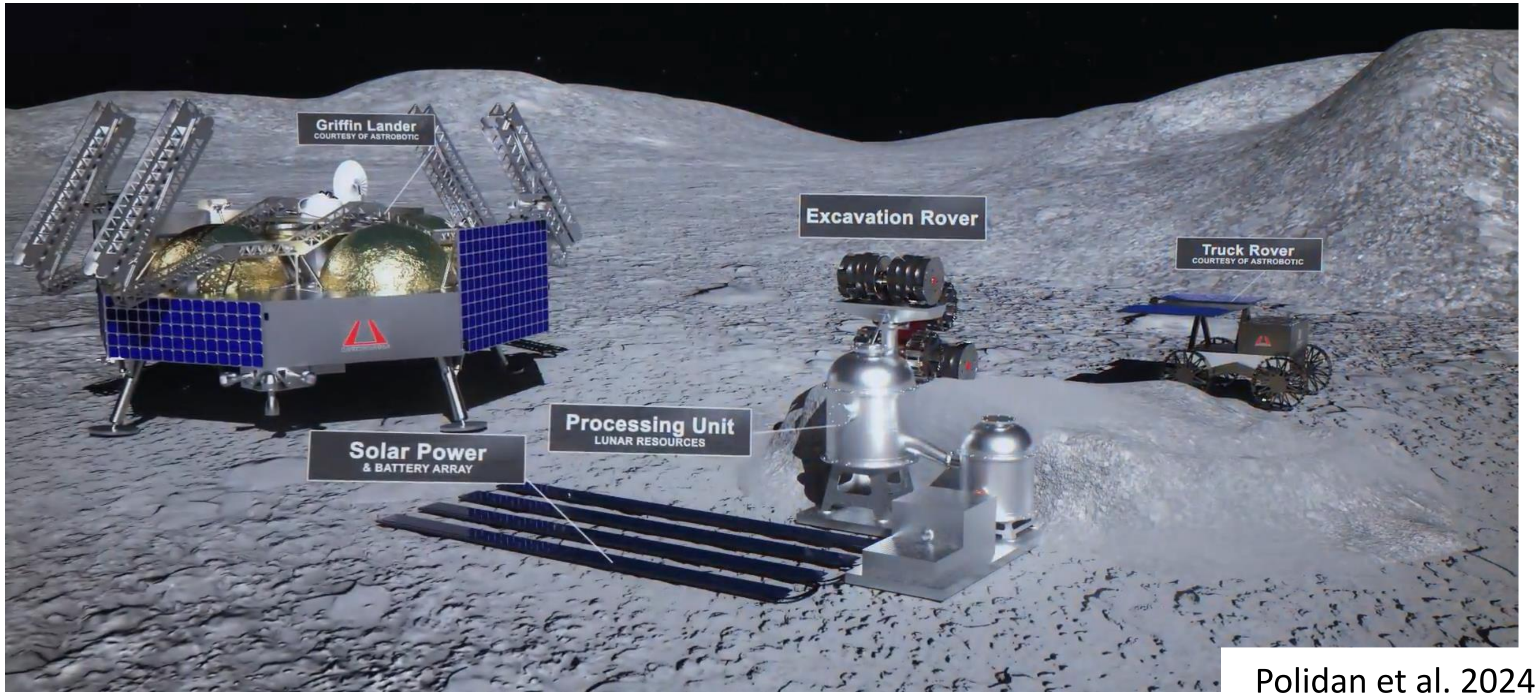
Lunar far side requirements

- Redshift 30 corresponds to ~45 MHz; redshift 50 corresponds to ~30 MHz
  - Ionospheric *opacity* may not be a fundamental obstacle to observations at these frequencies
  - Ionospheric *refraction* massively complicates foreground removal and is almost certainly a practical impediment to collecting the ~20,000 hours of data required
- Allowable levels of residual (i.e. missed) RFI for Epoch of Reionization experiments are very stringent: < 1 mJy per 1000 hours (Wilensky et al. 2020)
  - Dark ages signals are fainter, tolerances will be even stricter
  - RFI excision techniques could still be effective, but generally need RFI to be detectable in the raw data

FarView

- 100,000 antenna array on the lunar far side
- Dipole antennas, power lines, and solar cell power systems manufactured in situ out of lunar regolith





Polidan et al. 2024

Conclusions

- Exoplanetary magnetospheres require observations below the cutoff frequency of the Earth's ionosphere and exquisite control of polarization systematics (including RFI source)
  - Interesting sensitivities should be achievable with ~100 antenna system
- 21 cm dark age power spectra require large collecting areas and long integration times
  - Interesting sensitivities should be achievable with ~100,000 antenna system but foregrounds must be controlled
- Once constructed, arrays can run with minimal intervention but human presence valuable for initial surveys and infrastructure

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