SSERVI NESS Site Visit

FARSIDE: A Low Frequency Radio Array on the Lunar Far Side

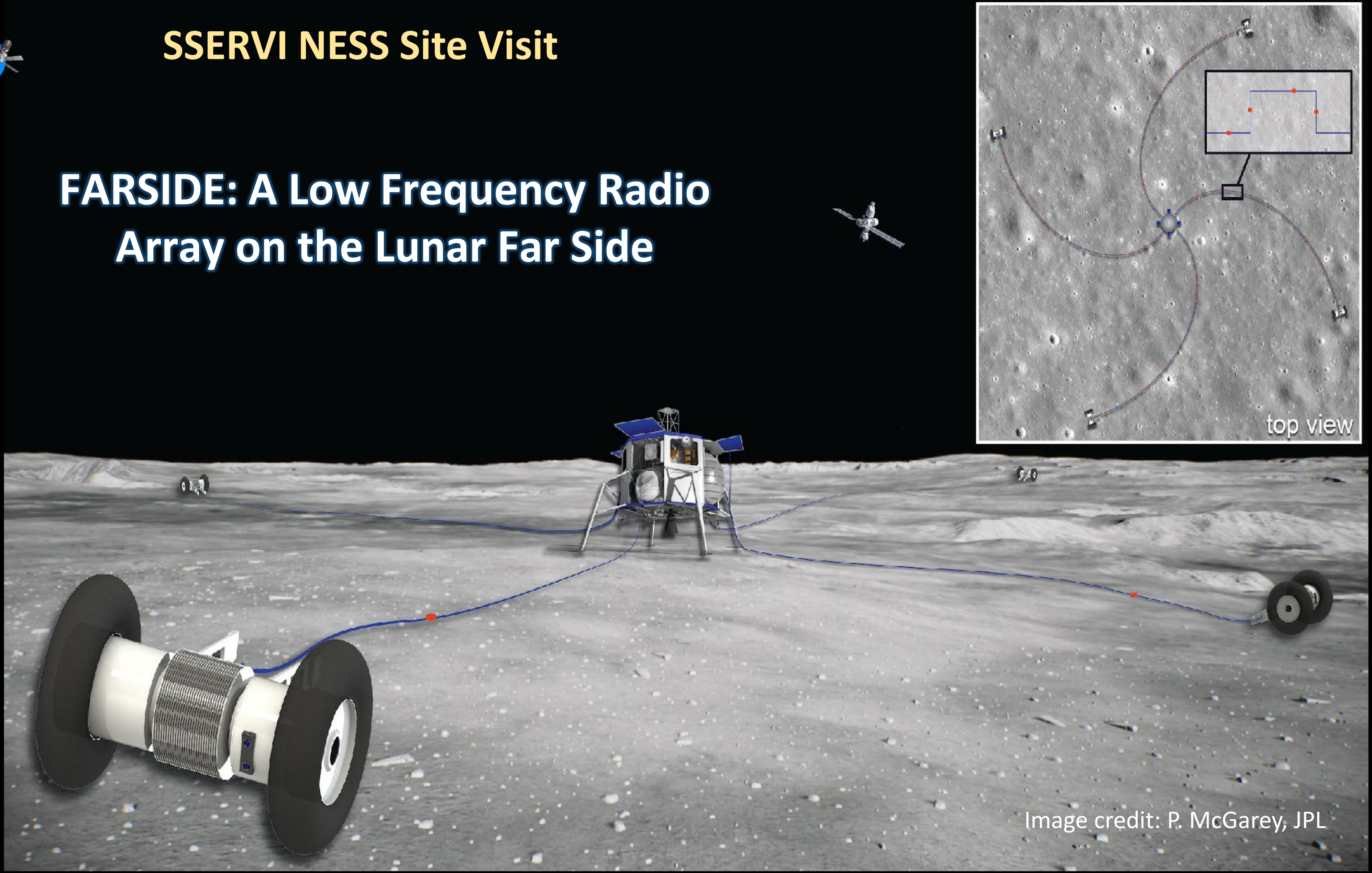

Image credit: P. McGarey, JPL

Gregg Hallinan
E-mail: *gh@astro.caltech.edu*

Caltech

Collaboration

NESS
Network for Exploration and Space Science

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BLUE ORIGIN

Steve Squyres, Alex Miller and the Blue Origin Team

Chuck Carter, KISS/Caltech

Magnetospheres and Space Environments of Habitable Planets

The Dark Ages and Cosmic Dawn

Simulation: Marcelo Alvarez

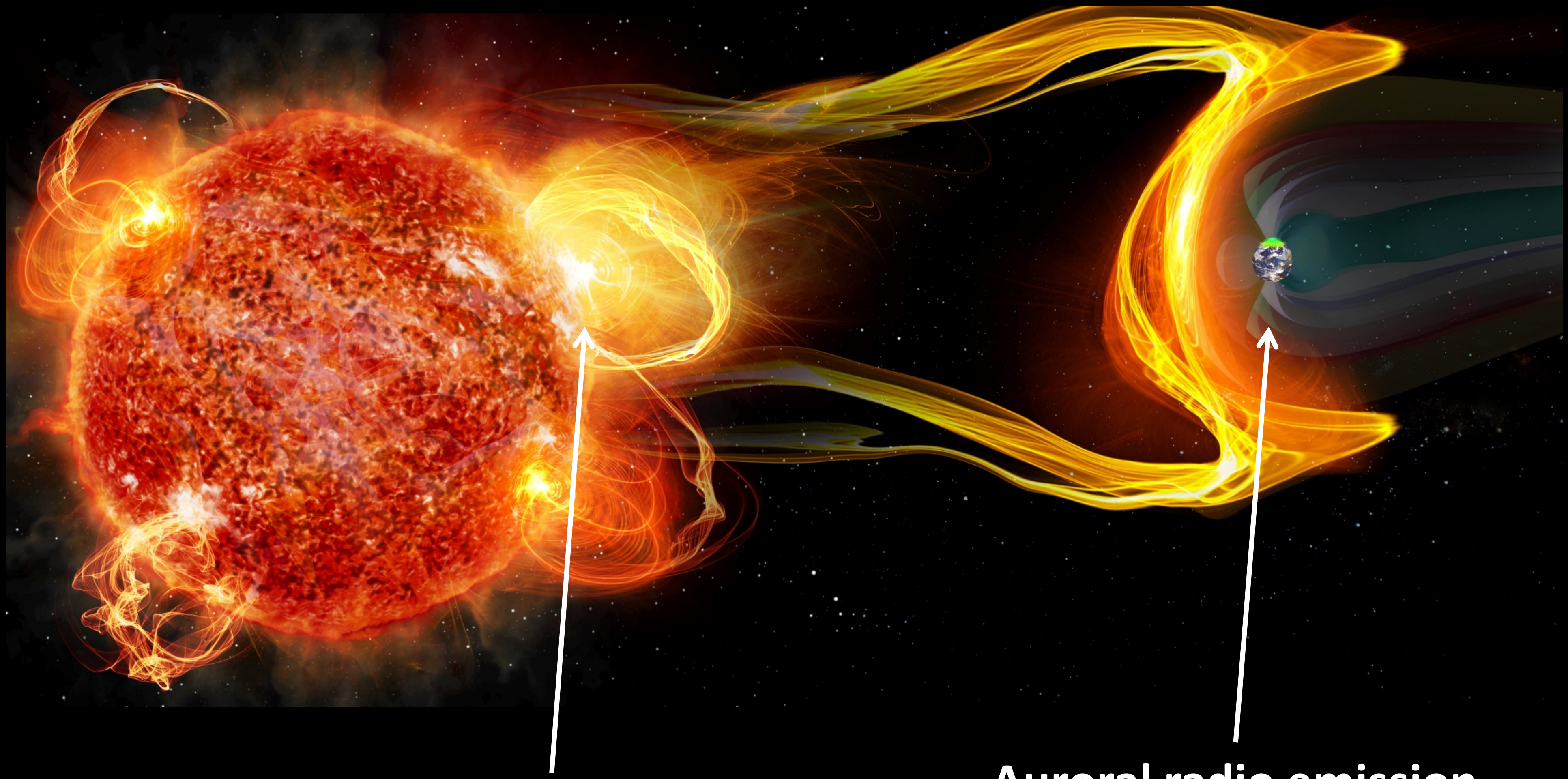
1.1 Science Traceability Matrix

Investigation	Goals	Objectives	Scientific Measurement Requirements: Physical Parameters	Scientific Measurement Requirements: Observables	Instrument Functional Requirements	Instrument Predicted Performance	Mission Functional Requirements Common to all Investigations	Mission Functional Requirements Specific to Each Investigation
Exoplanets and Space Weather	NASA Science Plan 2014 • Discover and study planets around other stars, and explore whether they could harbor life. New Worlds, New Horizons (2010 Decadal Survey) • Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet? • Discovery area: Identification and characterization of nearby habitable exoplanets. Exoplanet Science Strategy (National Academies of Sciences 2018) Goal 2: to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside. • The presence and strength of a global-scale magnetic field is a key ingredient for planetary habitability.	E1: Determine the prevalence and strength of large-scale magnetic fields on rocky planets orbiting M dwarfs and assess the role of planetary magnetospheres in the retention and composition of planetary atmospheres and planetary habitability.	Planetary magnetic field strength (proportional to frequency). Local stellar wind velocity. Planetary rotation period and assessment of the presence of a convective interior for a sample of rocky planets orbiting M dwarfs out to 10 pc.	Planetary radio flux: < 250 μJy (in the 150 kHz–250 kHz band). Frequency range: 150 kHz–1 MHz band. Polarization (IQUV stokes parameters)	**Noise Equivalent Flux** (for 60 second integration): 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** < 25 kHz **Temporal Resolution:** < 60 seconds **Minimum Frequency:** < 150 kHz **Maxmimum Frequency:** > 20 MHz **Number of Frequency Channels in band:** > 1000 **Polarization:** Full Stokes radio telescope or array on lunar farside with < 5% uncertainty **Sky Coverage:** > 5,000 sq. degrees Any other driving requirements with sidelobes? UV coverage? Confusion?	**Noise Equivalent Flux:** 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** 25 kHz **Temporal Resolution:** 60 seconds **Minimum Frequency:** 100 kHz **Maxmimum Frequency:** 40 MHz **Number of Frequency Channels in band:** 1400 **Polarization:** Full Stokes radio telescope or array on lunar farside (to avoid ionosphere and RFI), operational from 300 kHz to 10 MHz. [5% uncertainty] **Sky Coverage:** 10,000 sq. degrees	**Location:** Latitude and longitudes within 65 degrees of the anti-Earth point (required to suppress RFI from Earth by −80dB).	**Observation time:** > 1000 hours
		E2: Determine whether the largest stellar flares are accompanied by comparably large CMEs that can escape the corona of the star to impact the space environment of orbiting exoplanets. E3: Determine the space weather environment of rocky planets orbiting M dwarfs during extreme space weather events and assess whether such events play a decisive role in atmospheric retention and planetary habitability. E4: Determine the impact of extreme space weather events on exoplanets orbiting Solar type (FGK) stars and assess whether such events play a decisive role in atmospheric retention and planetary habitability.	Stellar radio bursts from particles accelerated in magnetic fields that vary with frequency due to their local plasma environment.	Radio burst dynamic spectrum: sensitivity 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz over 60 seconds. Frequency range: 150 kHz–35 MHz band.	**Noise Equivalent Flux** (for 60 second integration): 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** < 25 kHz **Temporal Resolution:** < 60 seconds **Minimum Frequency:** <= 100 kHz **Maxmimum Frequency:** > 35 MHz **Number of Frequency Channels in band:** > 1000 **Sky Coverage:** > 5,000 sq. degrees			
Cosmology	"Explore how (the Universe) began and evolved" NASA Science Plan (2014) "What is the nature of dark matter?" Astro2010 "Resolve the structure present during the dark ages and the reionization epoch" NASA Astrophysics Roadmap	C1: Determine if excess cooling beyond adiabatic expansion in standard cosmology and exotic physics (e.g., baryon-dark matter interactions) are present in the Dark Ages with > 5σ confidence.	Redshift-dependent *mean* brightness temperature variation of the cosmic radio background at the level of −100 mK due to the spin-flip transition of neutral hydrogen. Redshift range approx. (50 < z < 130)	Brightness temperature: a −40 mK absorption feature between 11–28 MHz against the cosmic radio background, globally averaged over > 10 deg^2. Frequency range approx. 11–28 MHz (corresponding to 50 < z < 130). Frequency resolution of 50 kHz to resolve the absorption feature and allow foreground & RFI mitigation and systematic checks. Astrophysical foreground mitigation to better than 10^5 level in spectral domain.	**Noise Equivalent Brightness Temperature Sensitivity:** < 20 mK **Antenna Beam Size:** field-of-view > 10 deg^2 (non-driving) **Antenna Beam Pattern Knowledge:** To a level of < 50 dB.	**Noise Equivalent Brightness Temperature Sensitivity:** 15 mK **Antenna Beam Size:** field-of-view > 10,000 deg^2 **Antenna Beam Pattern Knowledge:** 50 dB		**Observation time:** > 5000 hours

From the Probe Study Report: https://arxiv.org/abs/1911.08649

Low Frequency Radio Emission

Credit: Chuck Carter & Caltech/KISS



Type II radio bursts
traces density at CME shock

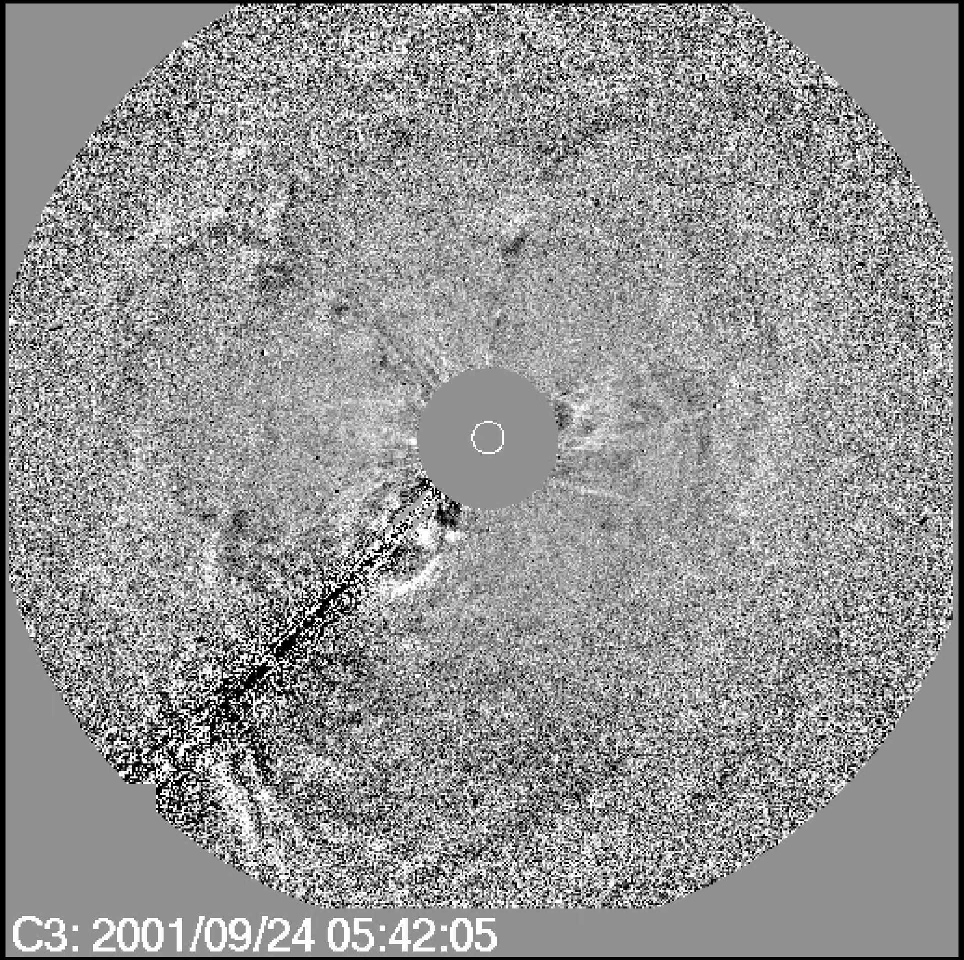
Auroral radio emission
measures magnetic fields

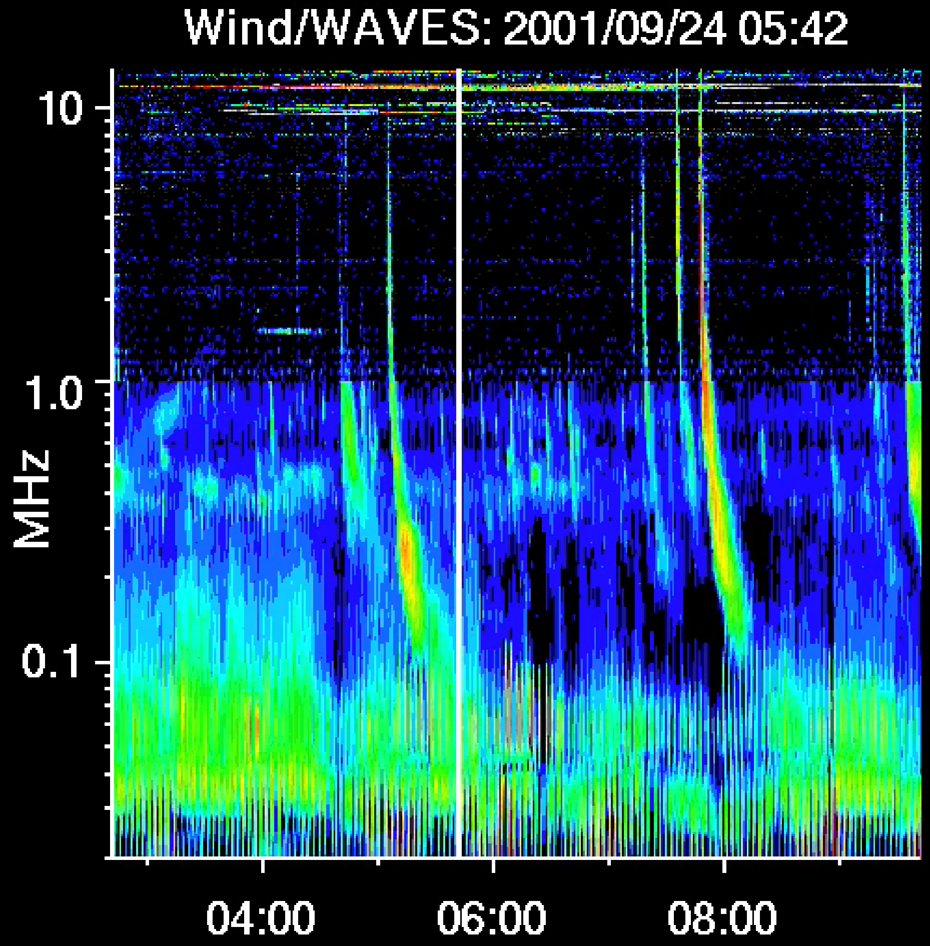
Credit: Chuck Carter and Caltech/KISS

Do M dwarfs produce super-CMEs?

<u>Can the magnetospheres of orbiting exoplanets support an atmosphere and biosphere</u>

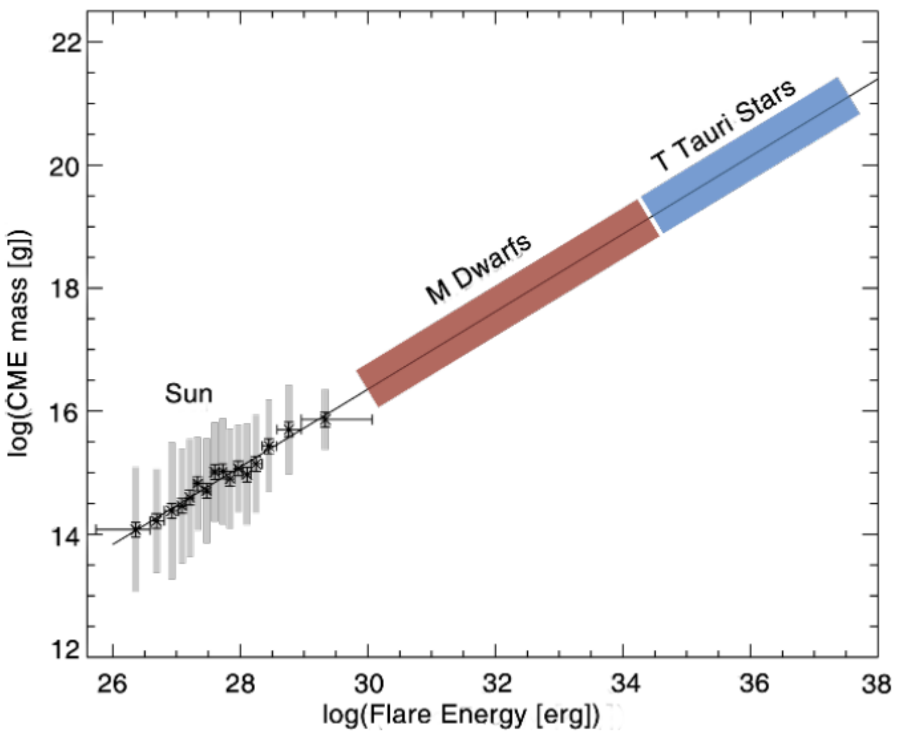
Type II Radio Bursts

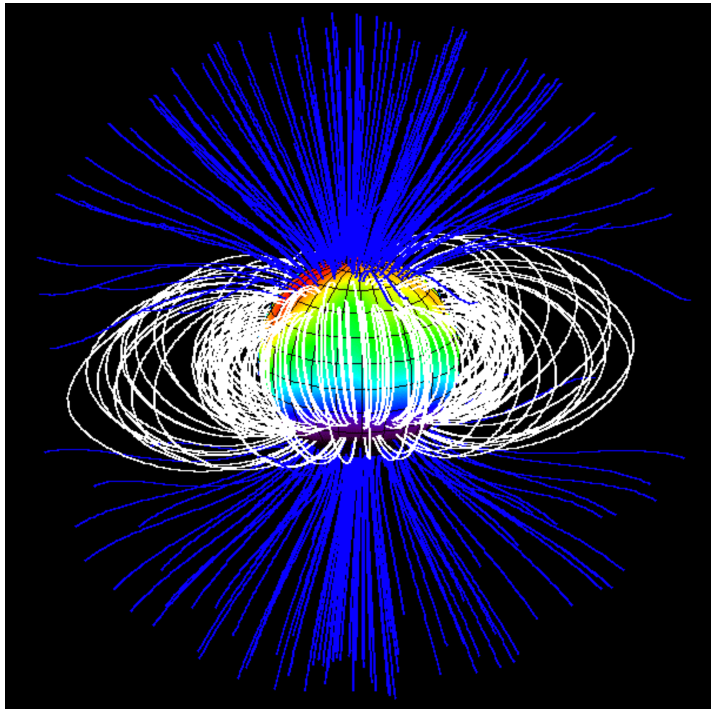




Plasma radiation: traces density

The Need for a Low Frequencies





Donati et al. 2006

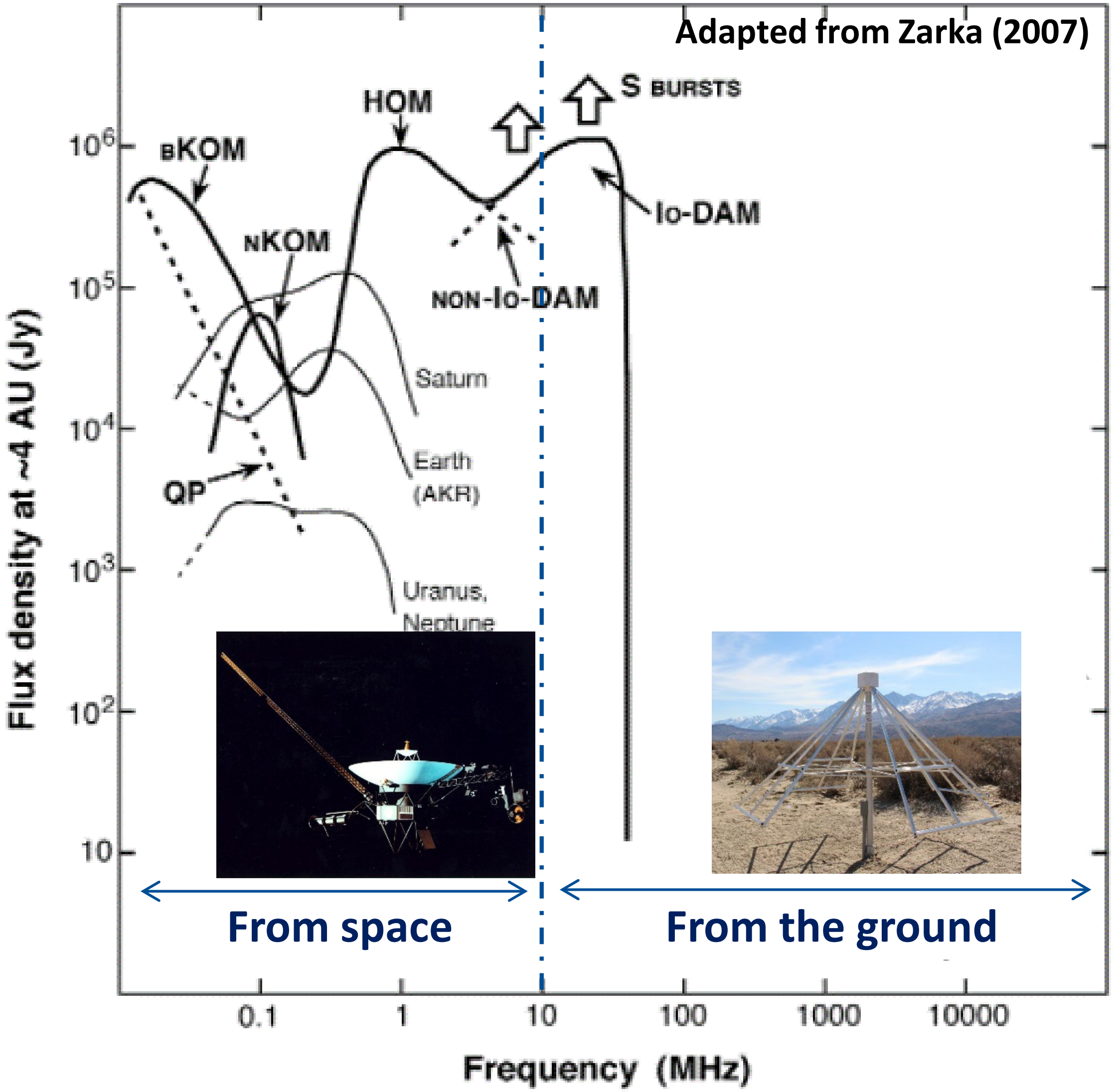
Adapted from Aarnio et al. 2012

No direct evidence of CMEs on any star other than the Sun to date

Magnetic field configuration may be play an important role (Alvarado-Gómez et al. 2018)

The Need for Low Frequencies

- **Electron cyclotron maser emission**
- **Frequency (MHz) = B_{Gauss} x 2.8**



The Need for a Paradigm Shift…

pan·op·tic

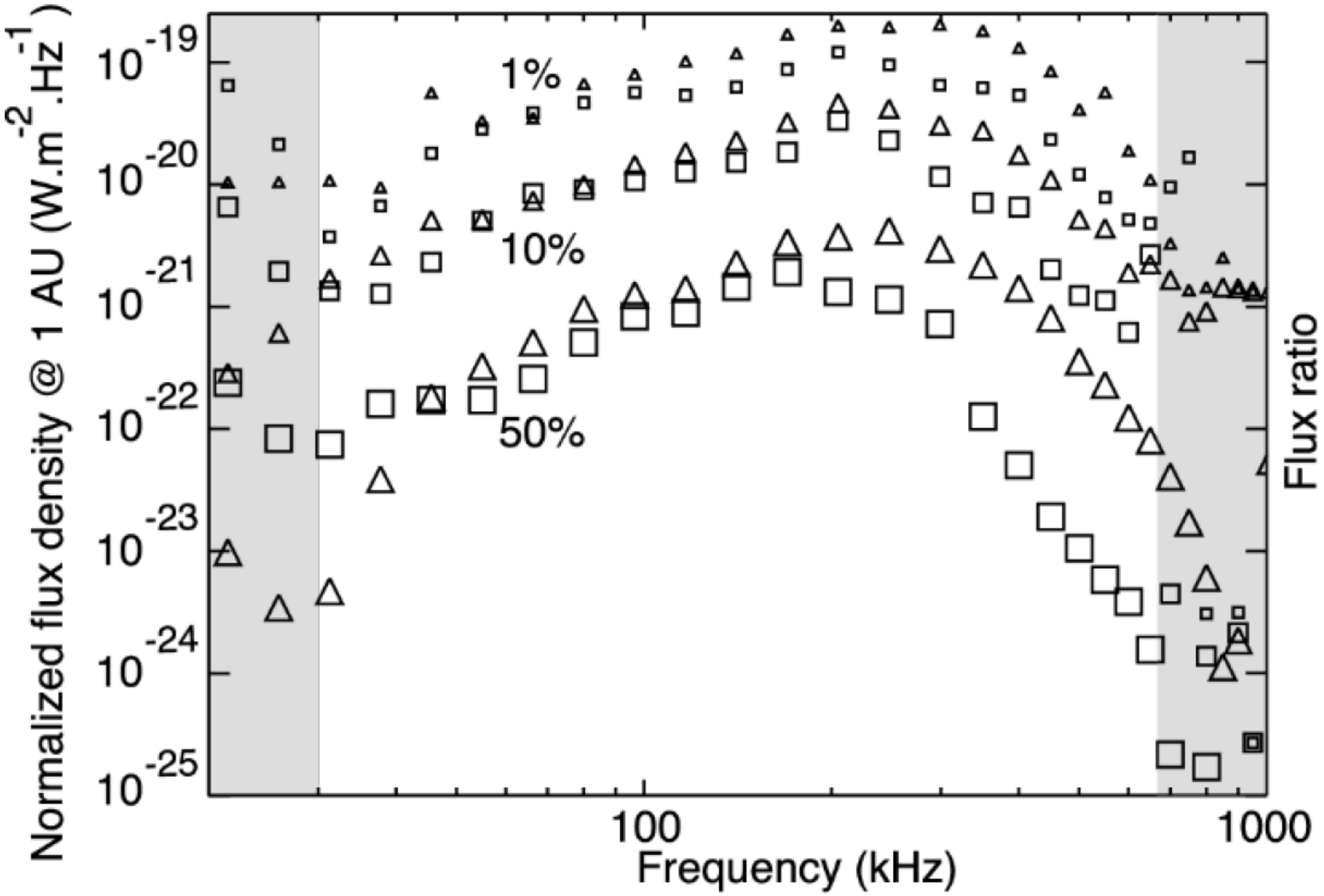
/paˈnäptik/

adjective

showing or seeing the whole at one view.

"a panoptic aerial view"

Earth's AKR is Highly Variable



Lamy et al. 2010

Requirements

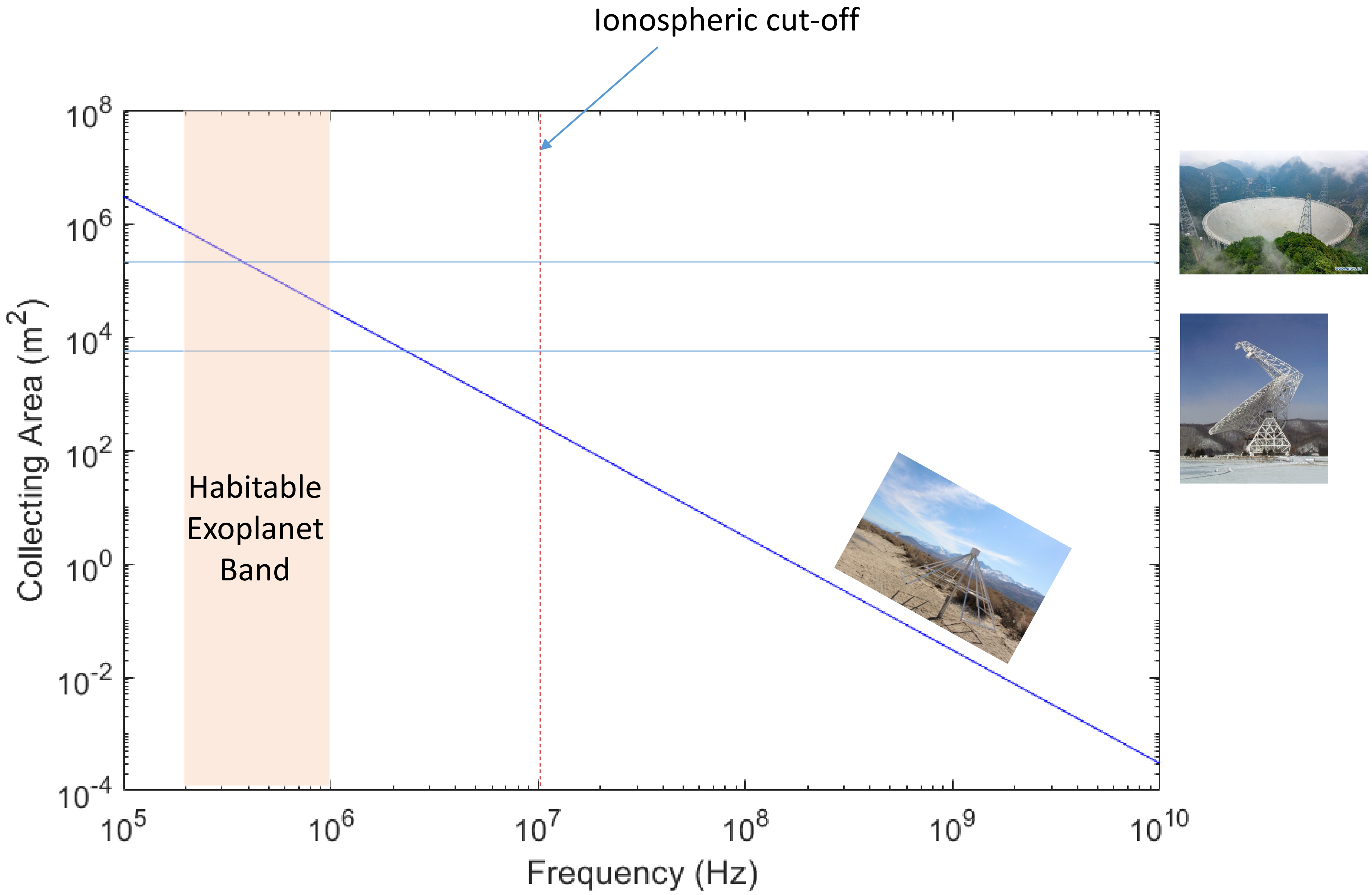
Need many km^2 of collecting area…

in space…

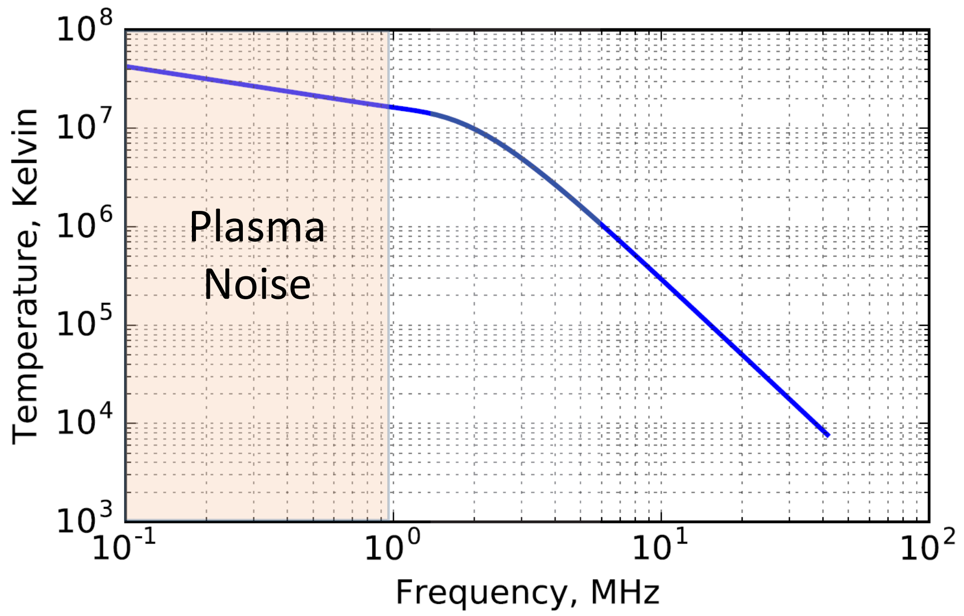
that can monitor 1000s of stellar systems simultaneously

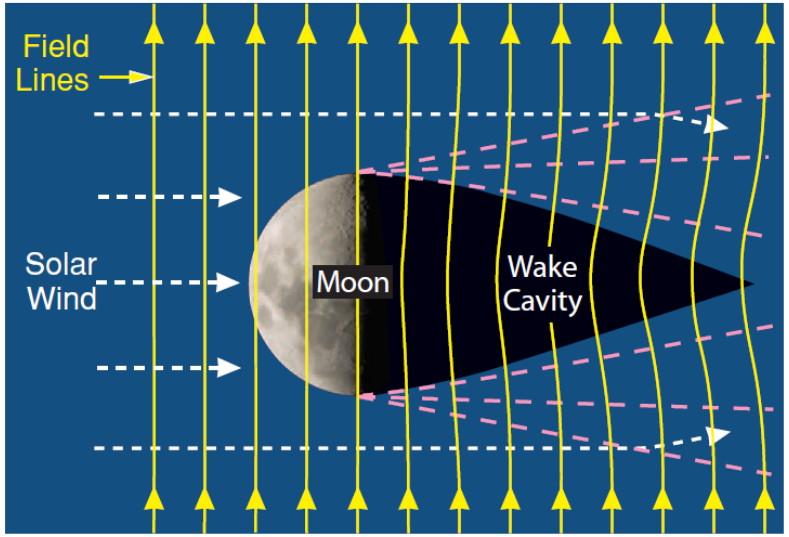
EASY!

What kind of Antenna?



The Lunar Farside





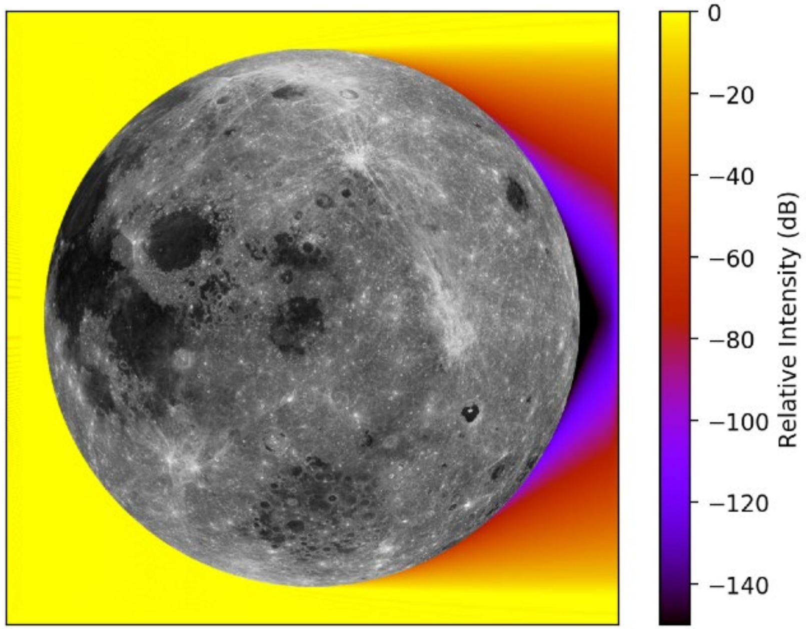
Credit: Andres Romero-Wolf

Credit: Steve Bartlett

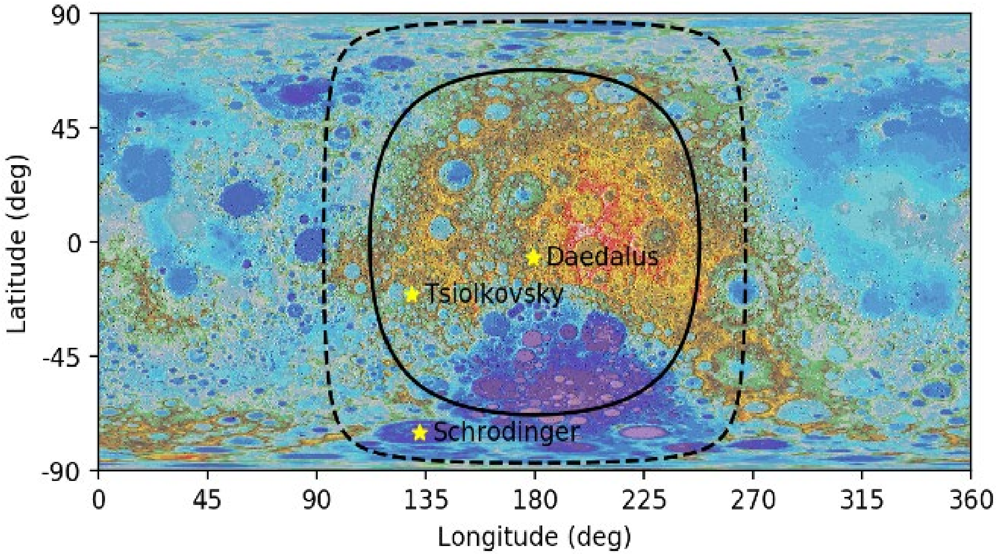
- **Lunar highlands regolith is thick, has low conductivity, and varies slowly with depth**
- **No ground screen required**

Simulations of the Radio Environment of the Moon

Bassett, Burns, et al. 2020, *Advances in Space Research*

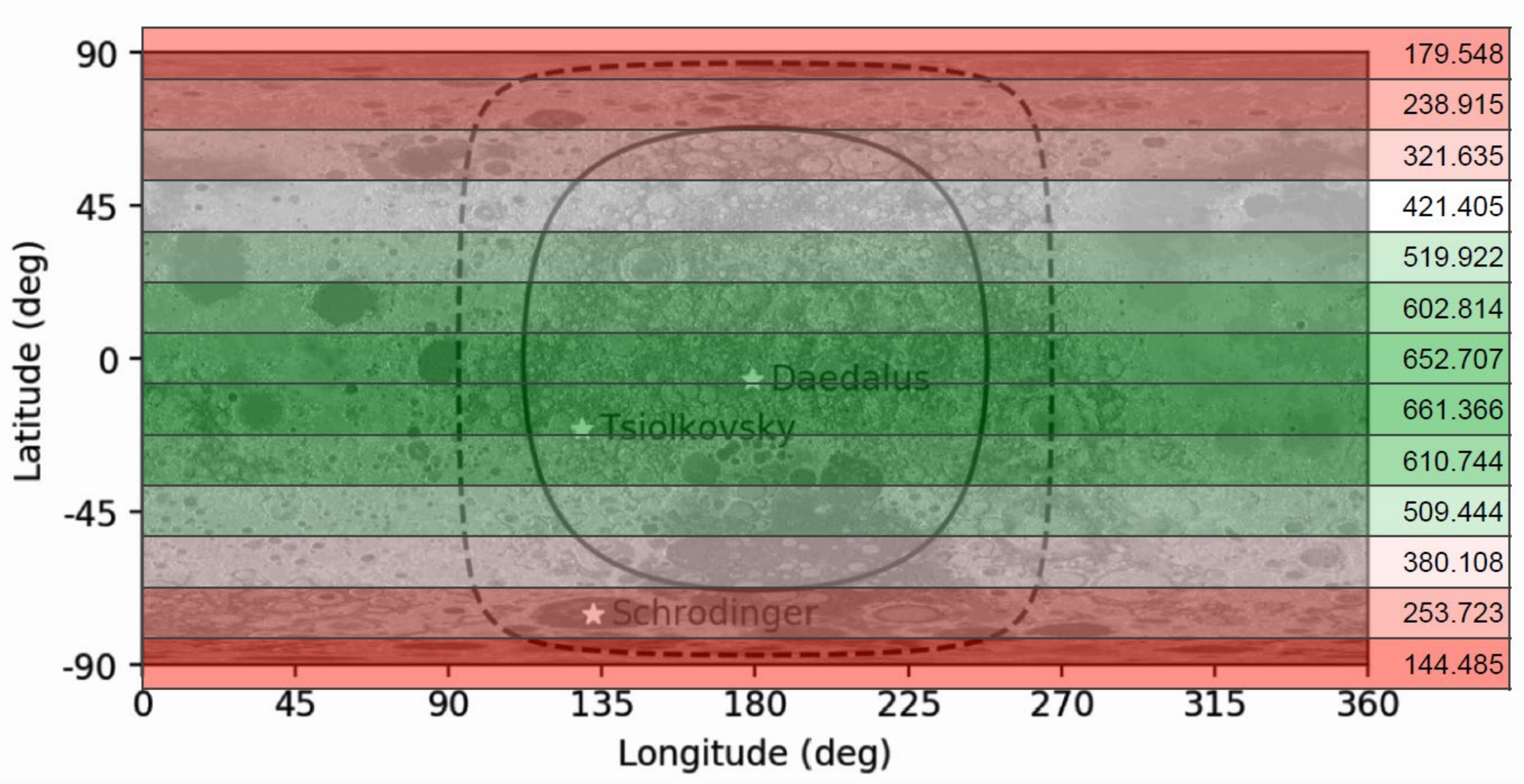


Two-dimensional numerical electrodynamics simulations show that the relative intensity of terrestrial radio waves incident on the Moon is highly attenuated behind the farside.



The "radio quiet" region at 100 kHz (solid) and 10 MHz (dashed) defined by $\geq$ 80 dB attenuation plotted over a map of the lunar surface.

Optimal Placement for Detecting Exoplanets



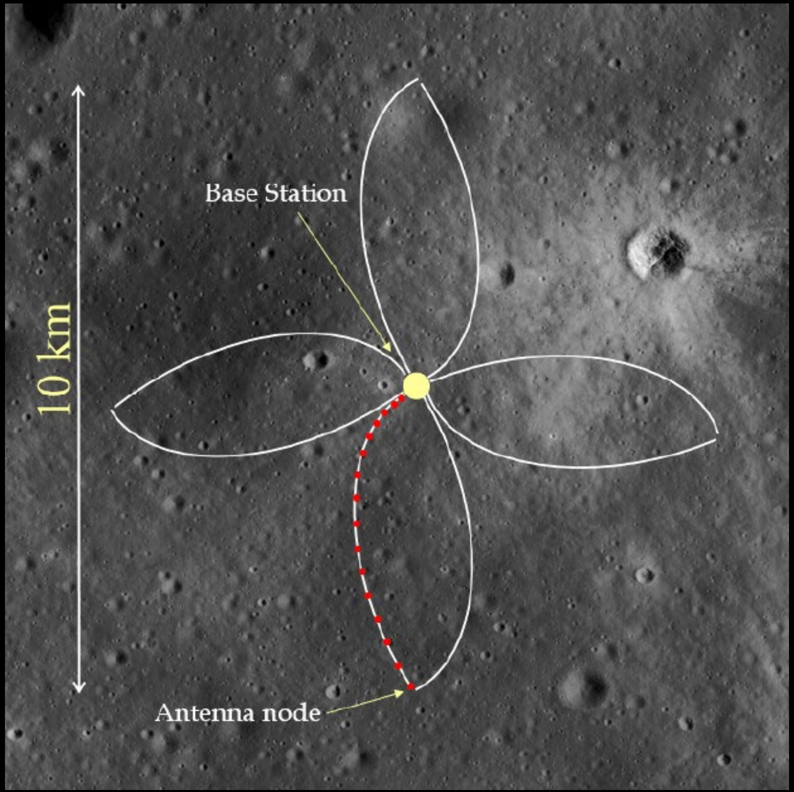
High School Senior
Jonathan Varghese

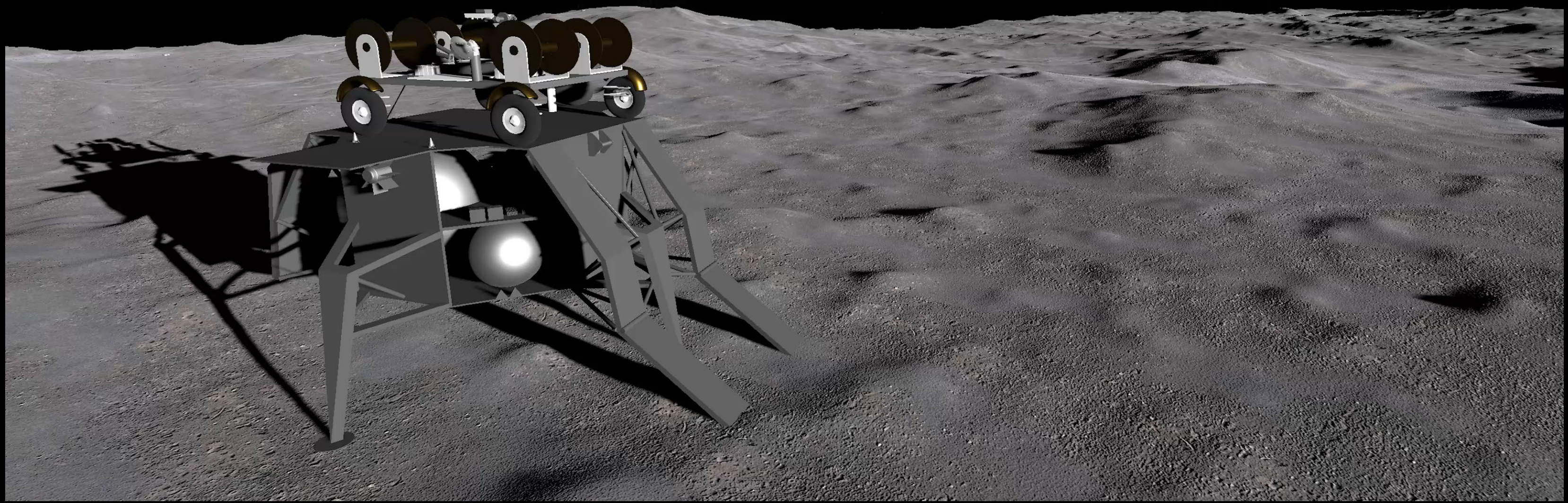
FARSIDE Timeline to Date

- Nov 2018: Directed probe study commenced – JPL selected as NASA Center
- Mar 2019: Overall architecture selected [Team X]
- Apr 2019: Follow up Rover, Base Station and Instrument studies [Team X]
- July 2019: Astro2020 APC White paper [https://arxiv.org/abs/1907.05407]
- Nov 2019: Final Probe Study Report submitted [https://arxiv.org/abs/1911.08649]
- April 2020: Commencement of JPL / Blue Origin Partnership
- Aug 2020: Planetary Science Decadal Review White Paper

Heritage from SunRISE and OVRO-LWA

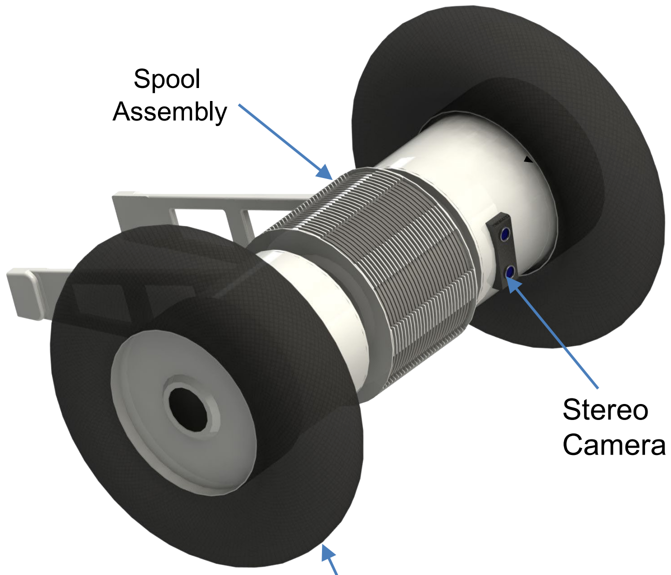
FARSIDE Initial Configuration

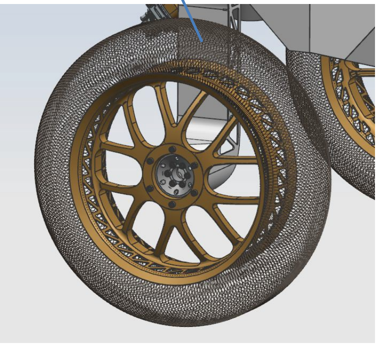




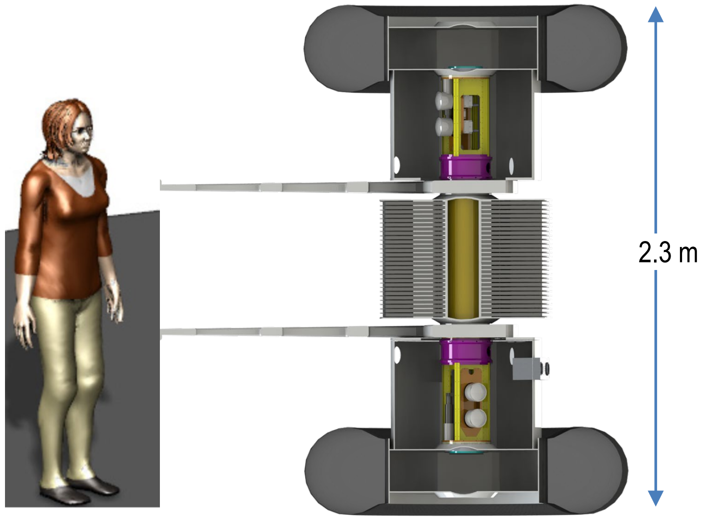
video credit: M. Walker, J. Burns,
University of Colorado Boulder

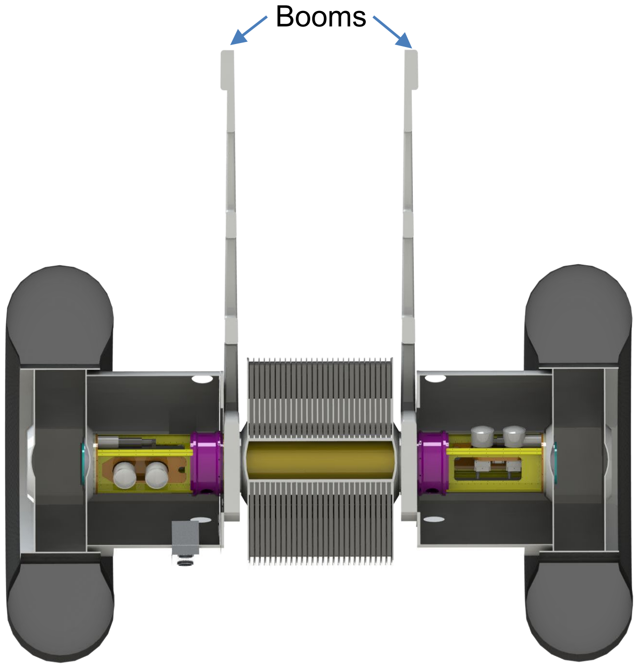
The Axel Rover





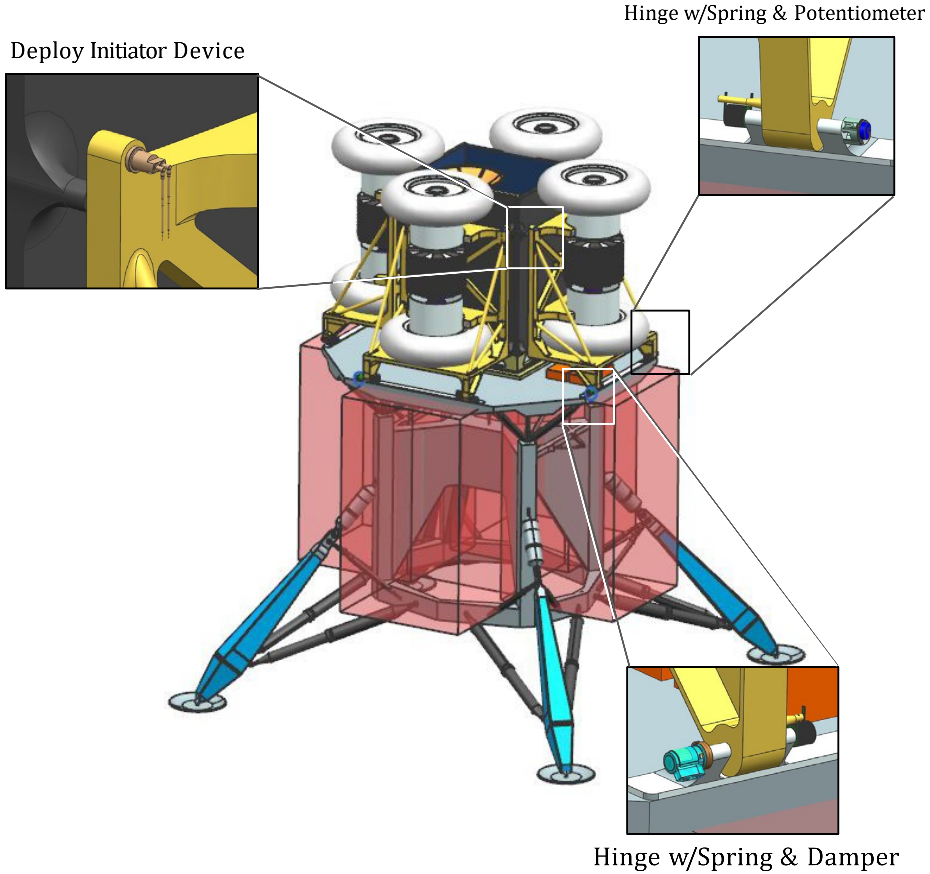
Apollo-style compliant
mesh wheel



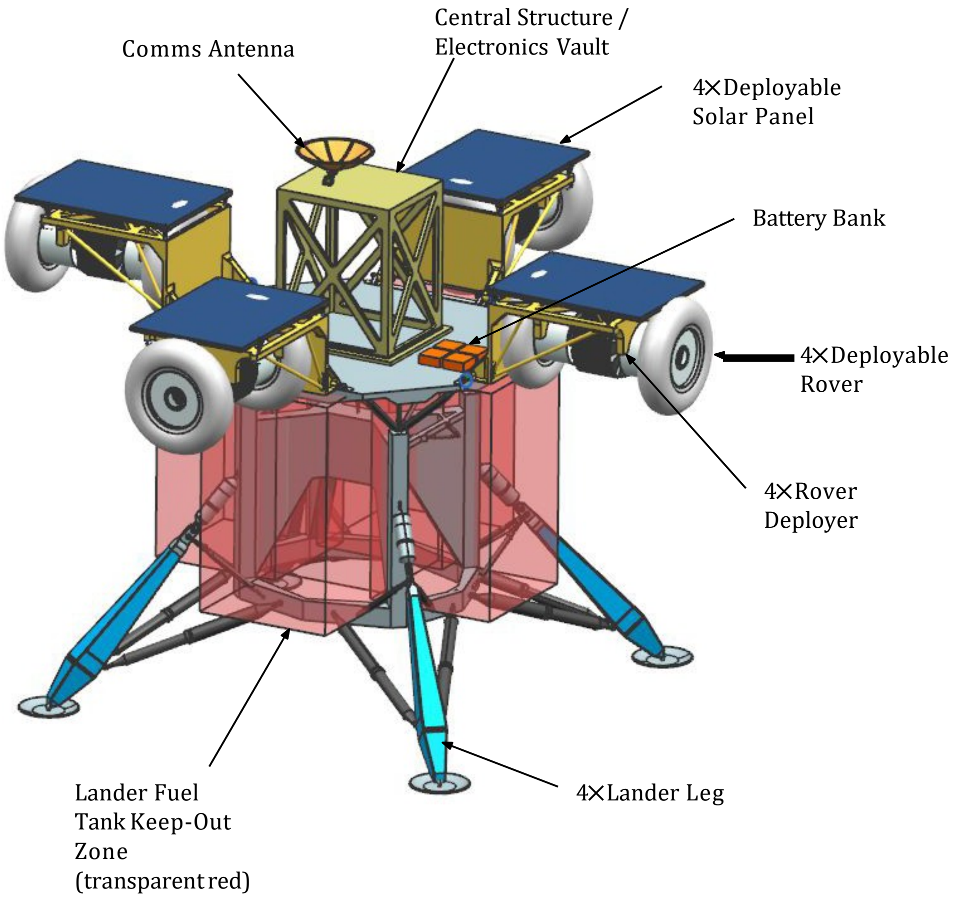


Lander/Rover Configuration Overview

Stowed/Landing Configuration



Mid-Deploy Configuration



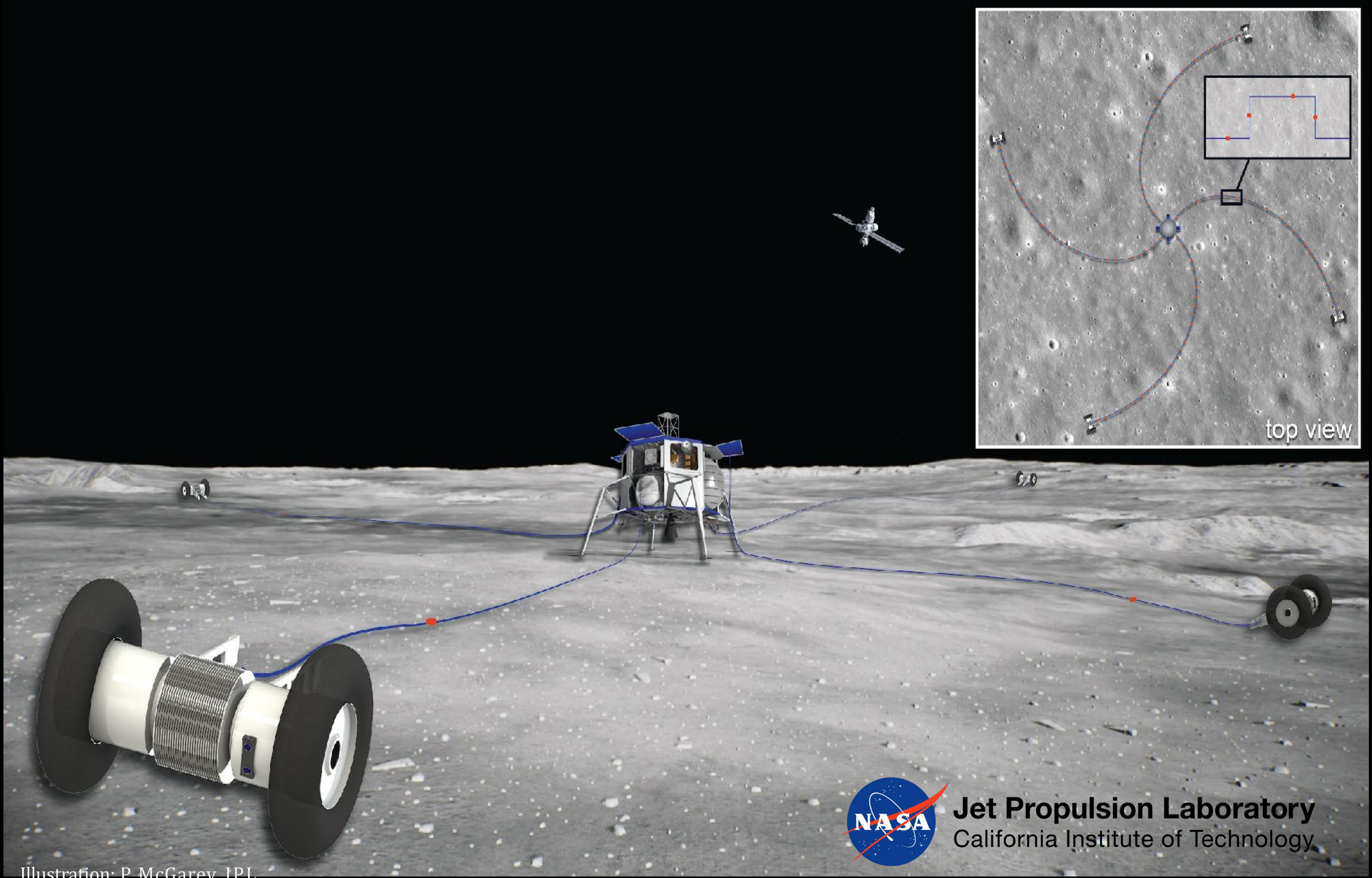
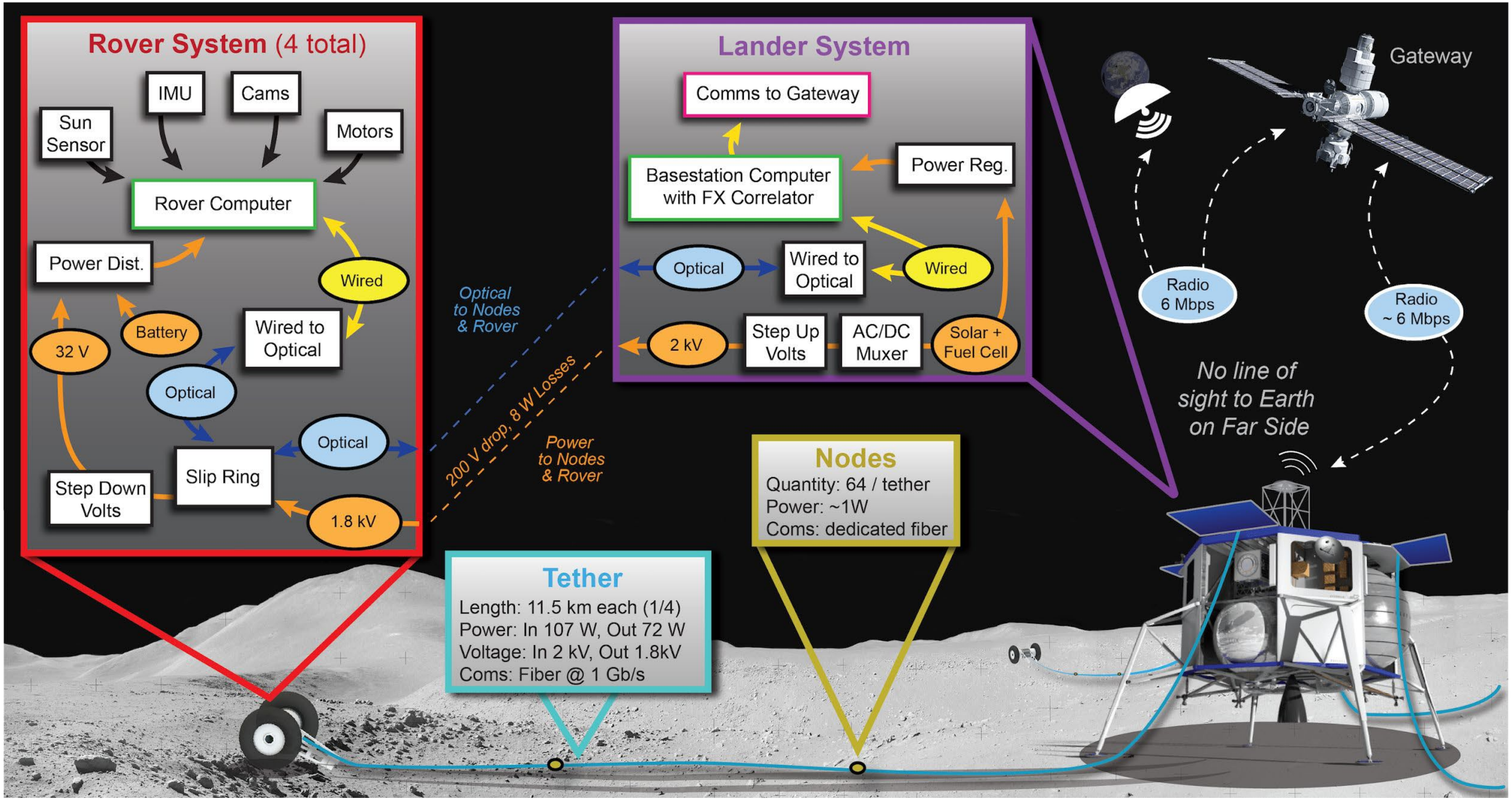


Illustration: P. McGarey, JPL

FARSIDE Mission Architecture

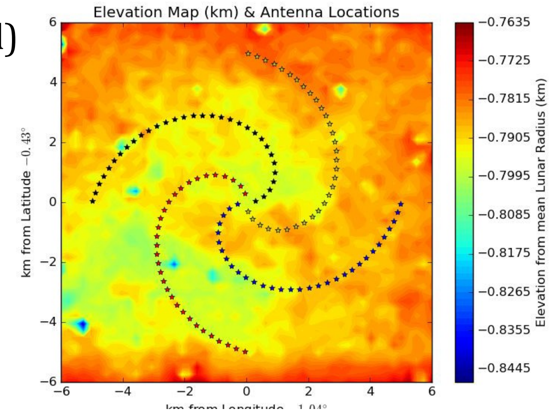
Frequencies: 100 kHz to 40 MHz

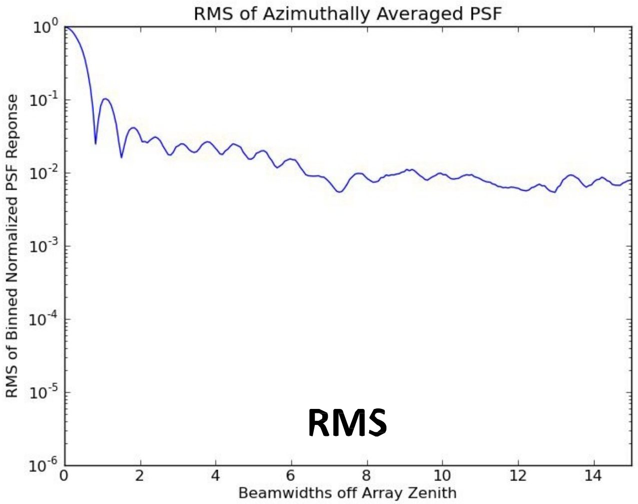


Tether/Antenna Response (Nominal)

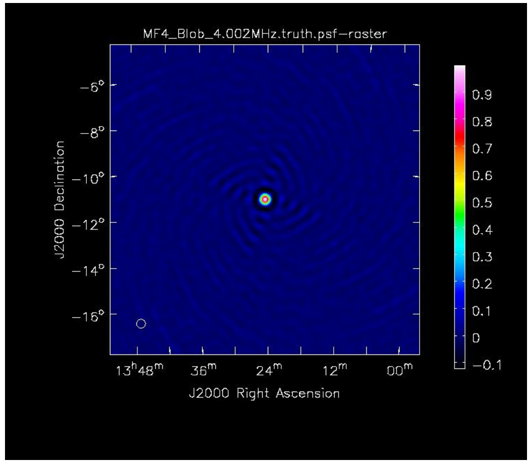
8.9 km arm length
4 spiral configuration (4 operational)

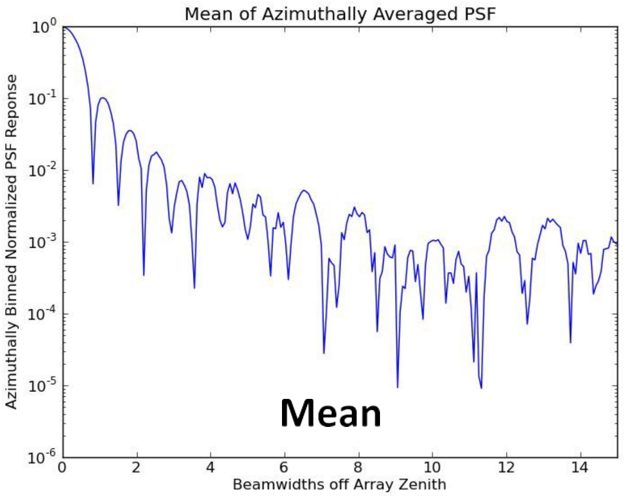
Frequency	Beam Width, arcsec
100 kHz	55,255.2
10 MHz	552.552
40 MHz	138.138
80 MHz	69.069

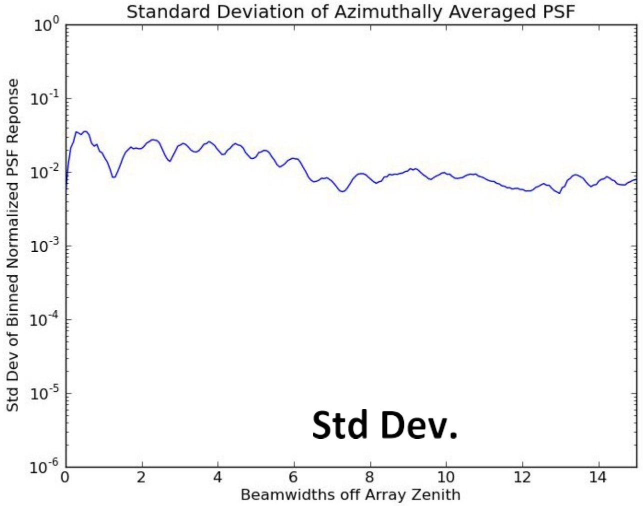




Point Spread Function

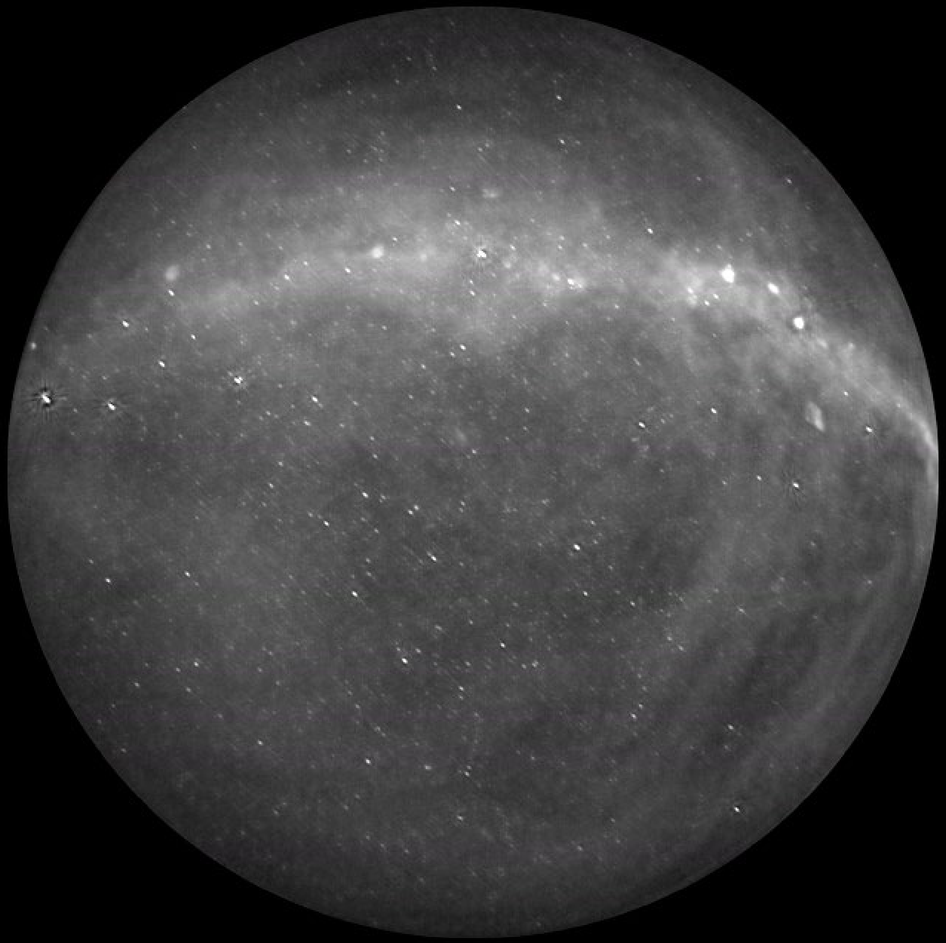






See talk by Alex Hegedus

Data Products

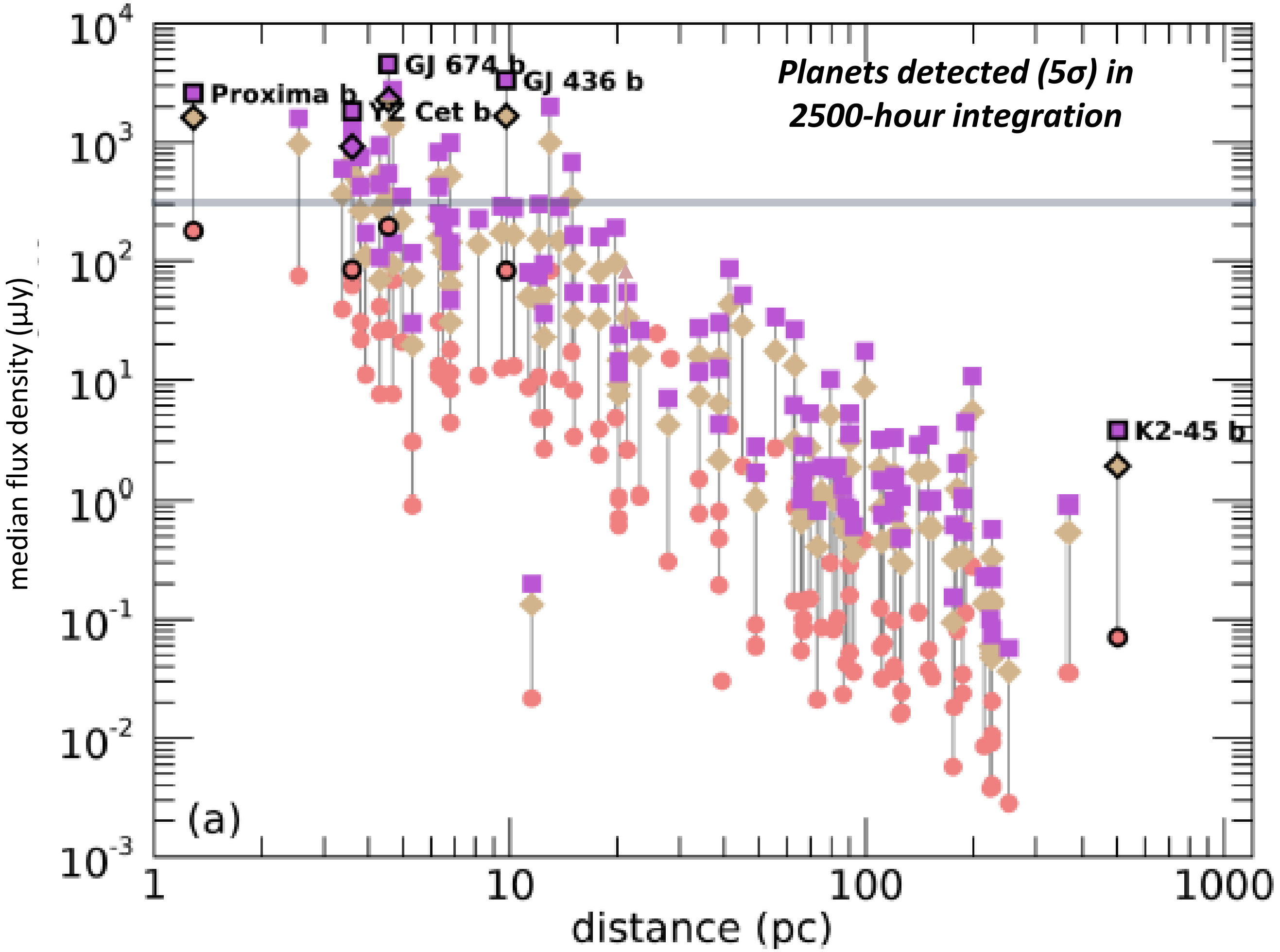


Data products are identical to OVRO-LWA, but 100x lower in frequency

Frequency range: 0 – 40 MHz (1400 channels)
Integration time: 60 s
All visibilities: 65 GB/day
All-sky imaging every 60 seconds (Stokes I and V)
Deep all-sky imaging every lunar day (no confusion noise!)

Credit: Marin Anderson and the OVRO-LWA team

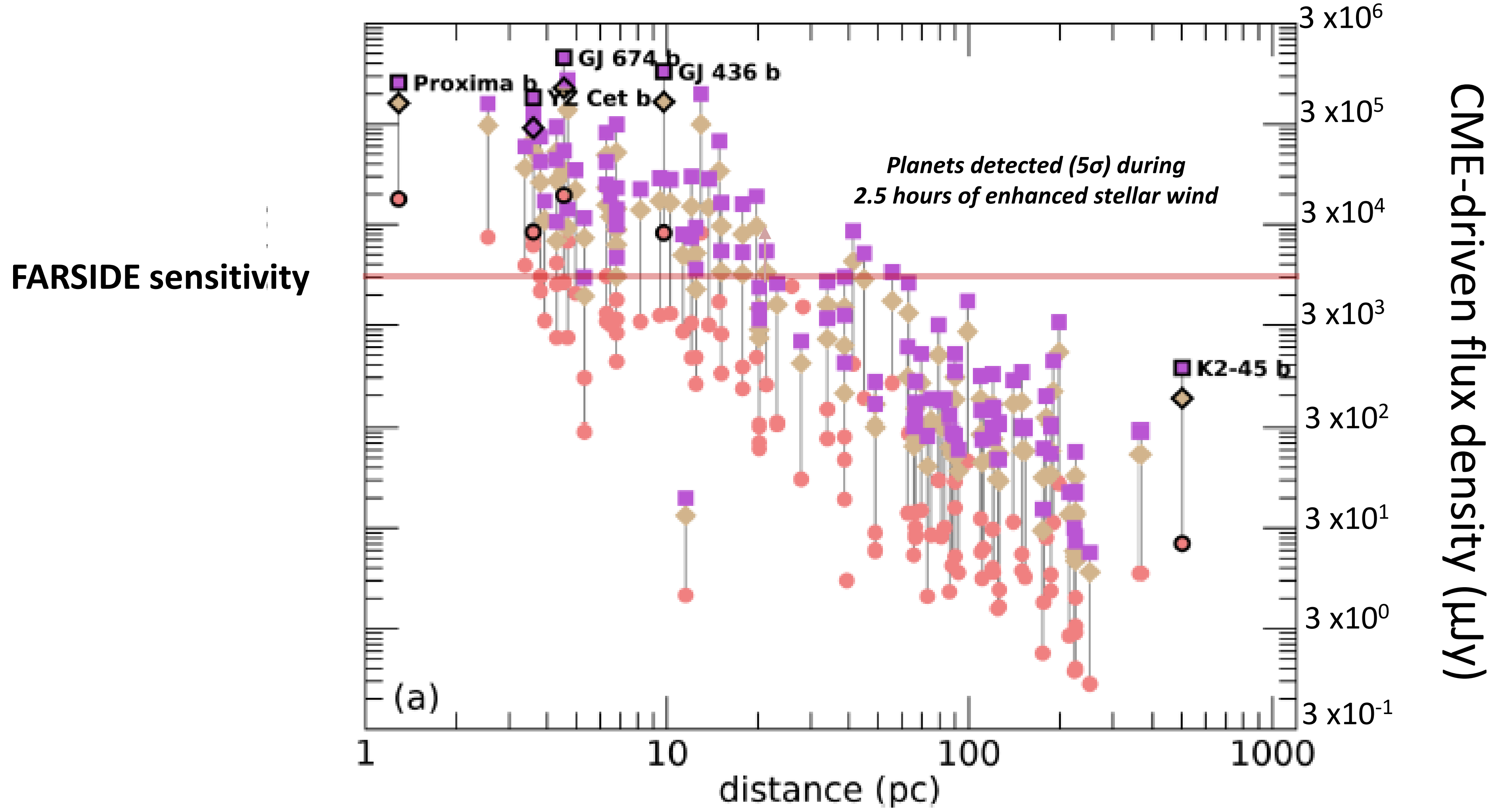
Median Exoplanet Radio Emission



FARSIDE sensitivity

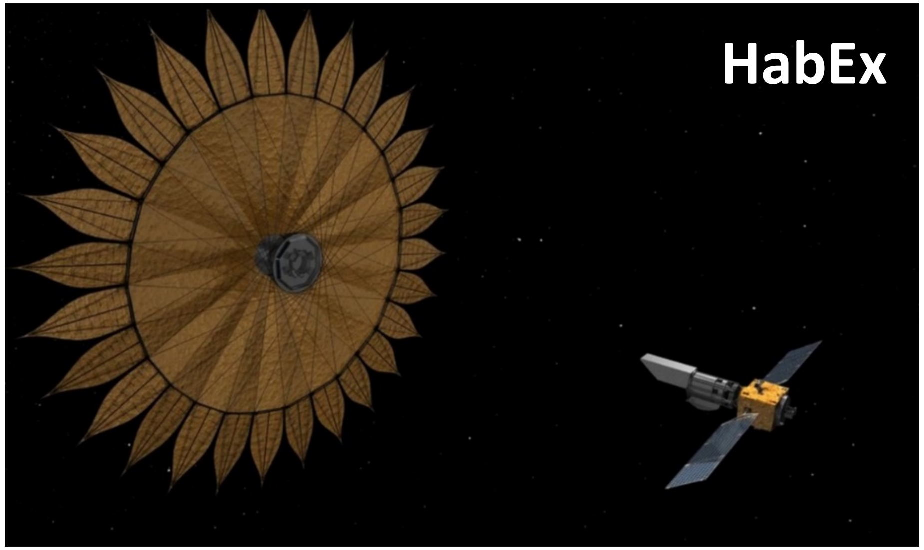
Adapted from Vidotto et al. 2019

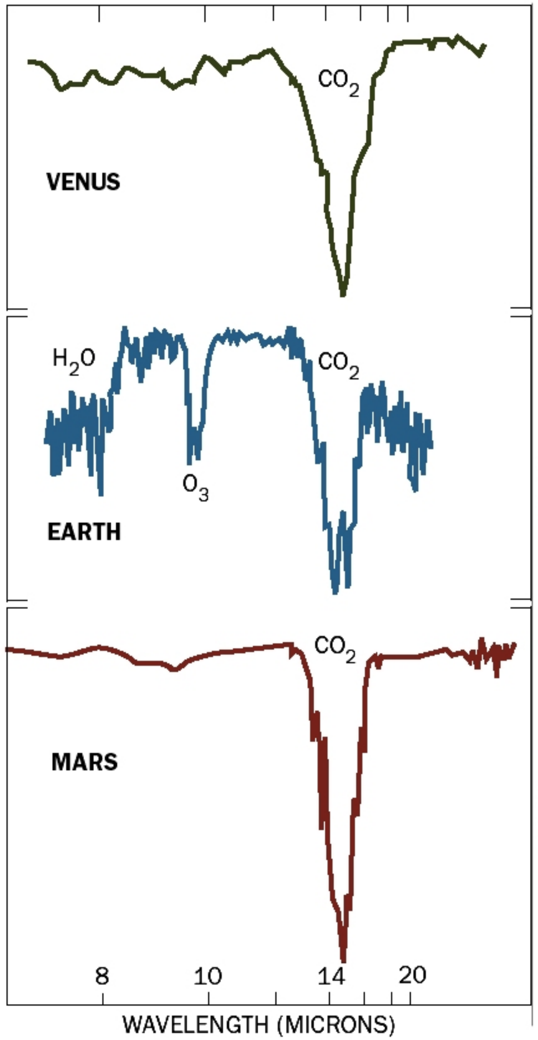
CME-driven Exoplanet Radio Emission



Adapted from Vidotto et al. 2019

Comparative Planetology





Additional Science

- First constraints on Dark Ages 21-cm power spectrum (ruling out exotic models)

- Heliophysics

- Monitoring of auroral processes and lightning at Jupiter, Saturn, Uranus and Neptune

- Searches for unknown large magnetized bodies in our solar system (e.g. Planet 9)

- Triggered spectroscopy of exoplanets experiencing geomagnetic storms

- Tomography of the ISM

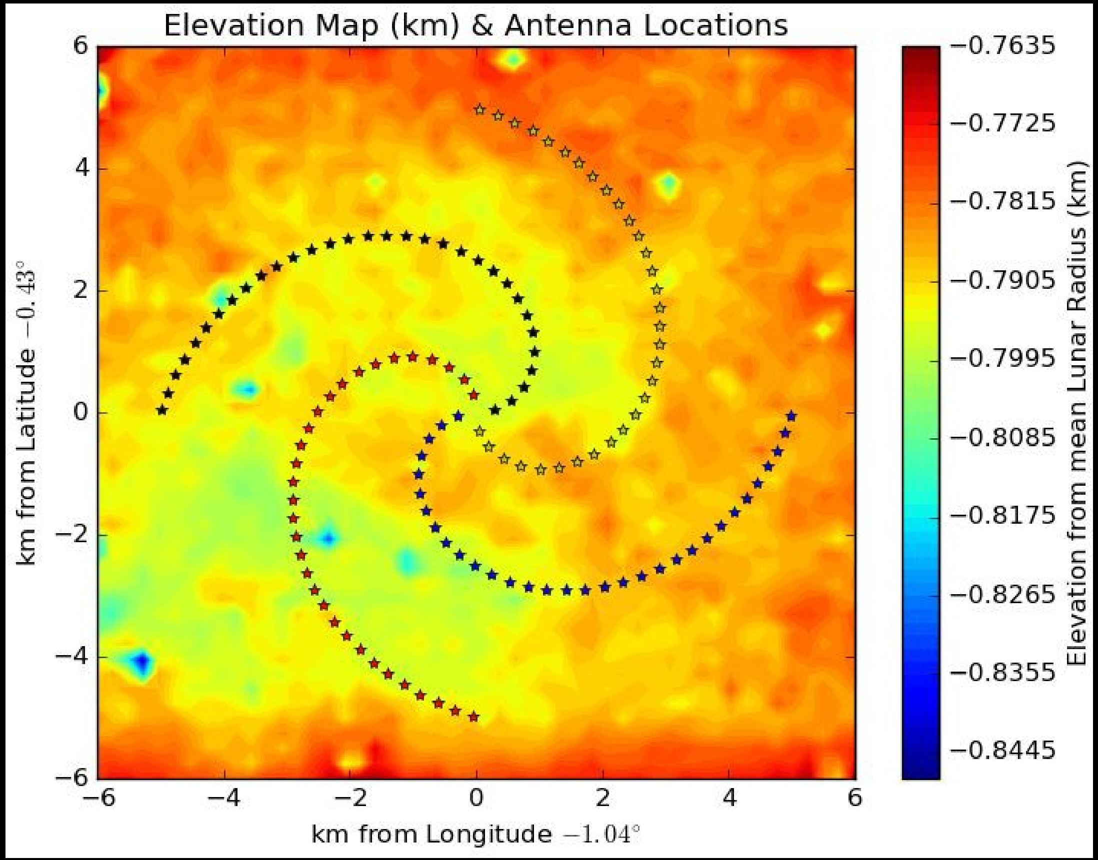
- Lunar Seismology

- SETI

- Serendipitous!

Lunar Seismology with Distributed Acoustic Sensing (DAS)

Credit: Joel Caswell for Caltech



i) What is the mantle structure and seismic activity at the far side

ii) Is there a lunar liquid core

Summary

- FARSIDE is proposed to consist of 128 dipole antennas on the lunar far side
- NASA-funded study to define architecture and feasibility
- Recent collaboration between JPL and Blue Origin has greatly improved the design
- FARSIDE will measure the magnetospheres of the nearest candidate habitable planets
- FARSIDE will detect the signature of the Dark Ages
- FARSIDE will characterize far side moonquakes and the size and properties of the lunar core
- FARSIDE will study solar CMEs and planetary aurorae and lightning