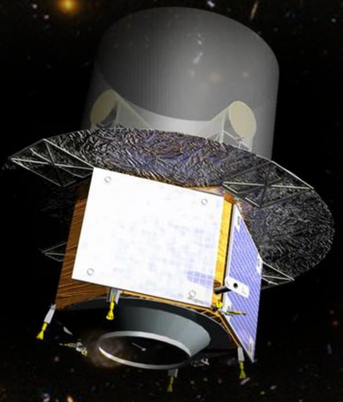
DARE

Low Frequency Radio Astronomy From Space

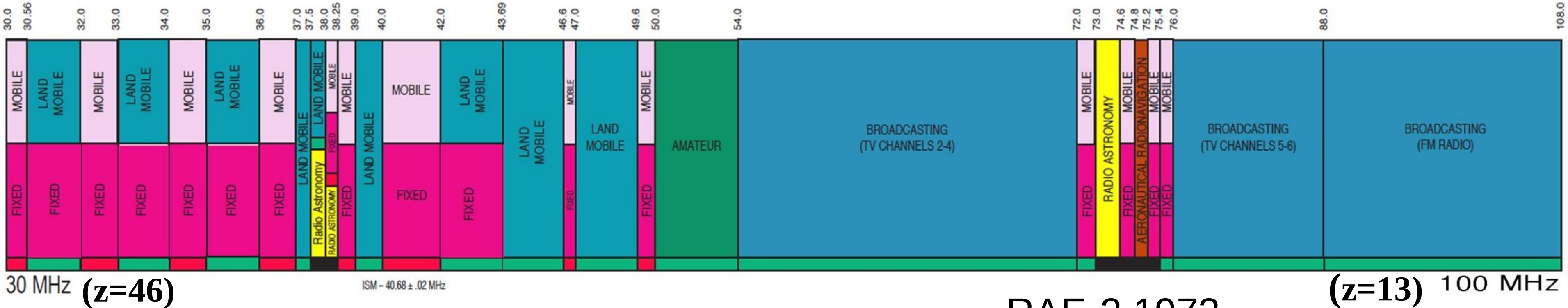
Jack Burns

University of Colorado Boulder

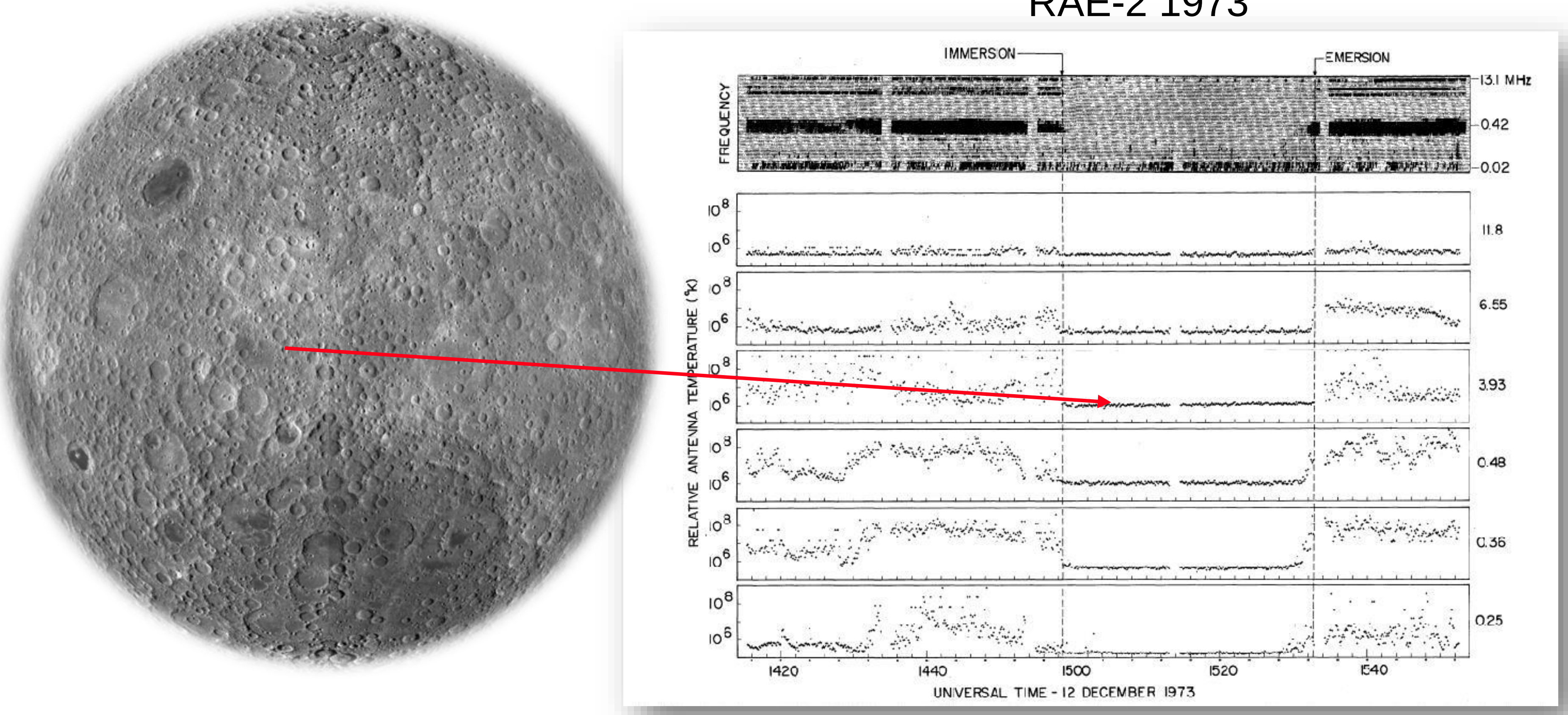


U.S. Radio/Millimeter/Submillimeter Science Futures III

Lunar Farside: No RFI or Ionosphere!

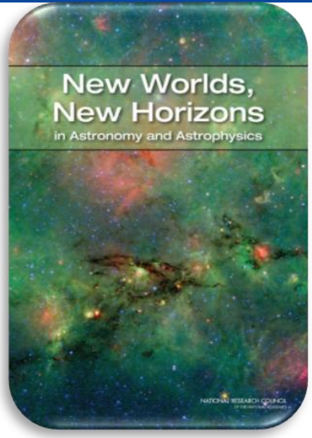


RAE-2 1973

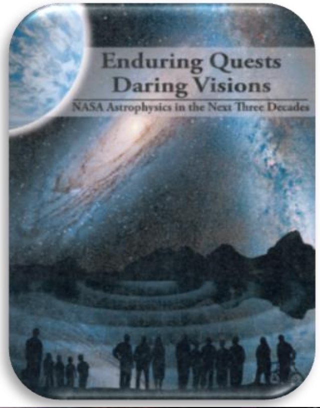


Astrophysics Decadal Survey & NASA Astrophysics Roadmap identify Cosmic Dawn as a top Science Objective

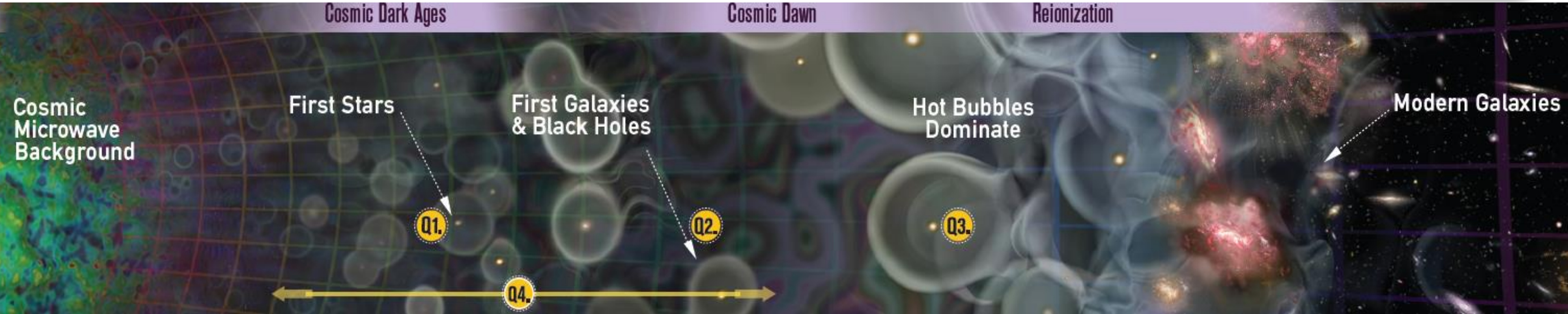
- ***New Worlds, New Horizons (NRC 2010):*** "A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?"



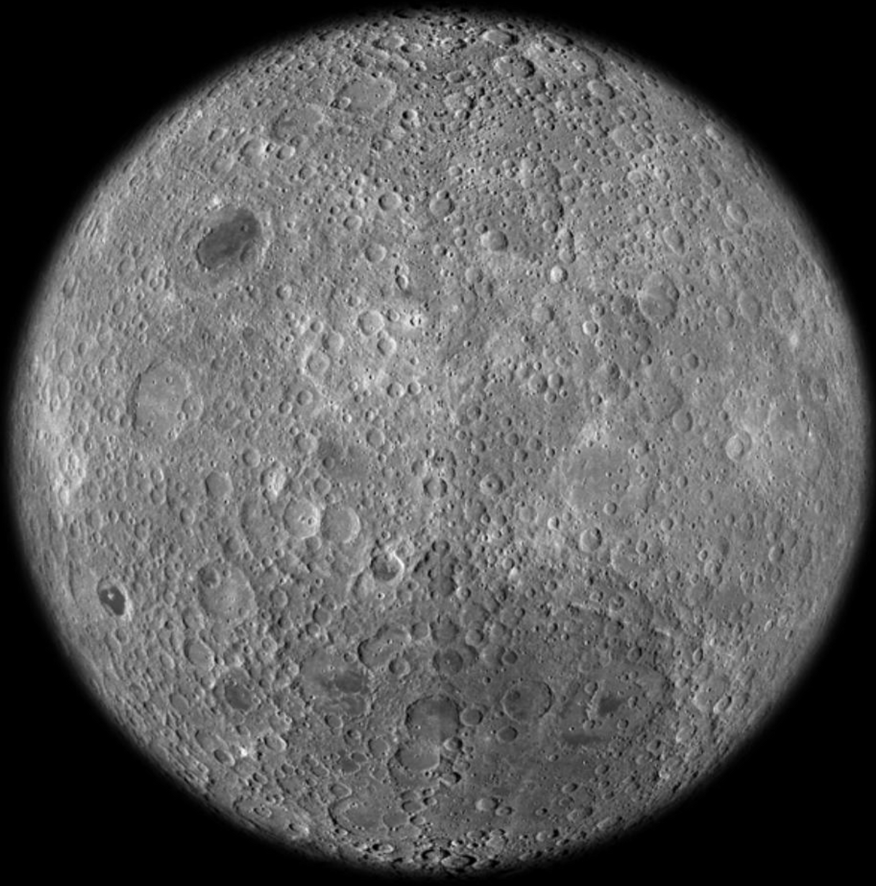
- ***NASA Astrophysics Division Roadmap (2013):*** How Does our Universe Work?
  - **Small Mission:** "Mapping the Universe's hydrogen clouds using 21-cm radio wavelengths via a *lunar orbiter* observing from the farside of the Moon".
  - **Visionary Era:** "*Cosmic Dawn Mapper* (21-cm lunar surface radio telescope array) … Detailed map of structure formation in the Dark Ages via 21-cm observations".

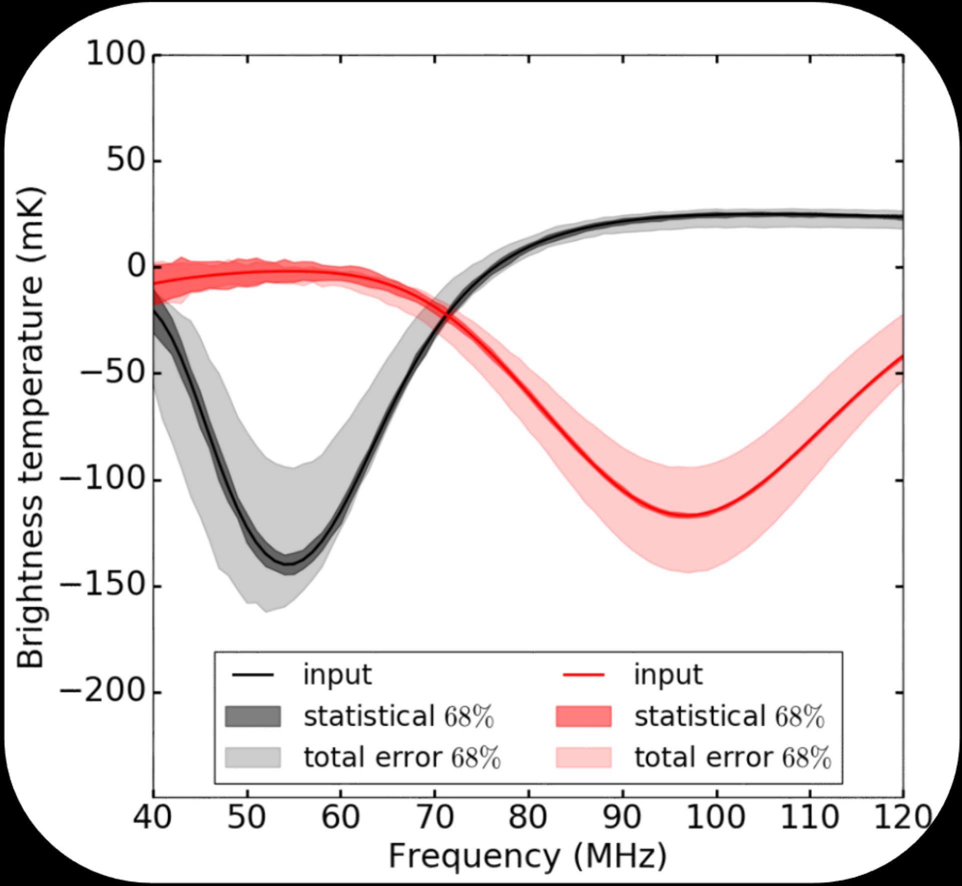


"What were the first objects to light up the Universe and when did they do it?" **NRC Astro 2020 Decadal Survey, New Worlds, New Horizons.**



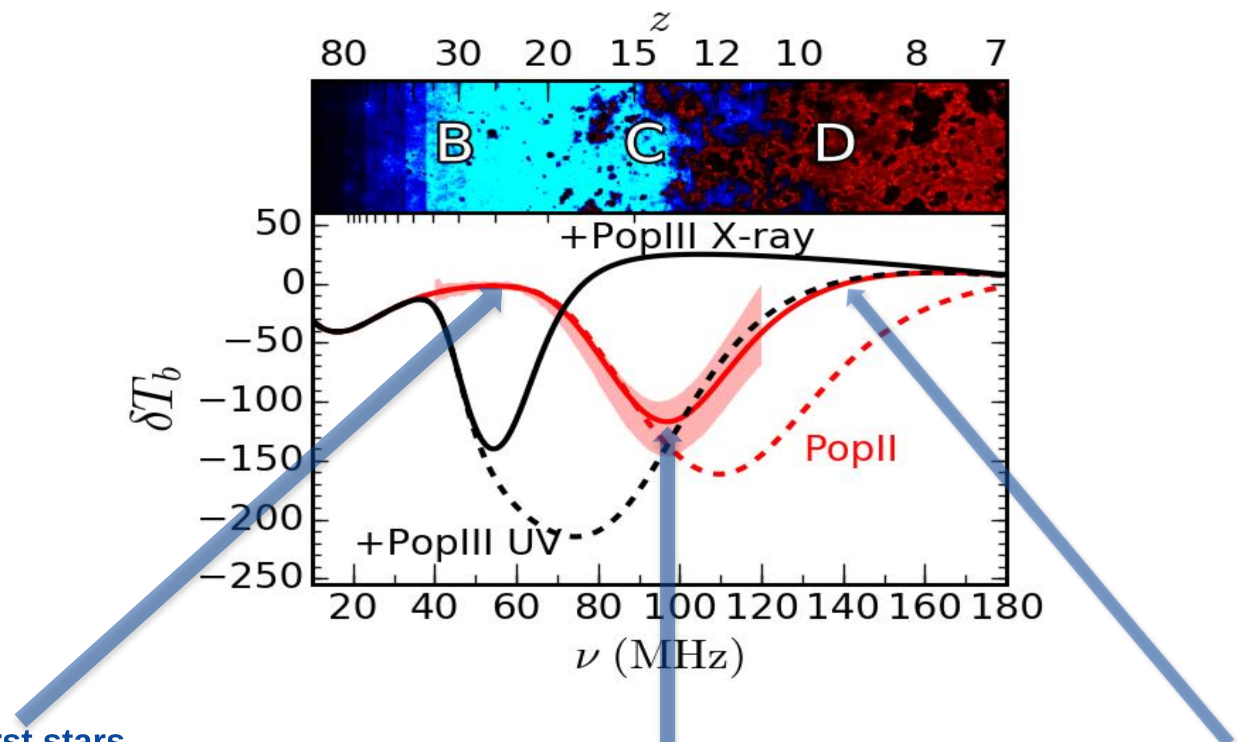
The 21-cm Global All-Sky Signal





The 21-cm Monopole Reveals the Birth & Characteristics of the First Stars & Galaxies

$$\delta T_B = 25 x_{HI} \left(\frac{1+z}{10}\right)^{1/2} \left(1 - \frac{T_{CMB}}{T_S}\right) \text{mK}$$



B: ignition of first stars

- When did the First Stars ignite? What were their characteristics?
- Is there evidence for exotic physics (e.g. Dark Matterr decay) in the Dark Ages?

C: heating by first black holes

- When did the first accreting black holes turn on? What were their characteristics?

D: the onset of reionization

- What was the history of Reionization in the early Universe?

Burns *et al.* 2017, ApJ, 844, 33
and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

DARE Project Team

Principal Investigator: Jack Burns, University of Colorado Boulder

Project Management & Mission Operations: NASA Ames Research Center: B. Hine & J. Bauman

Observatory Project Management: Ball Aerospace & Technologies Corp.: W. Purcell & D. Newell

Science Co-Investigators:

- Robert MacDowall, NASA GSFC, Project Scientist
- Richard Bradley, NRAO, Deputy Project Scientist
- Judd Bowman, Arizona State University
- Anastasia Fialkov, CfA
- Steven Furlanetto, UCLA
- Dayton Jones, Space Science Institute, Boulder
- Justin Kasper, University of Michigan
- Abraham Loeb, Harvard University
- Raul Monsalve, University of Colorado
- Jordan Mirocha, UCLA
- David Rapetti, University of Colorado Boulder
- Edward Wollack, NASA GSFC

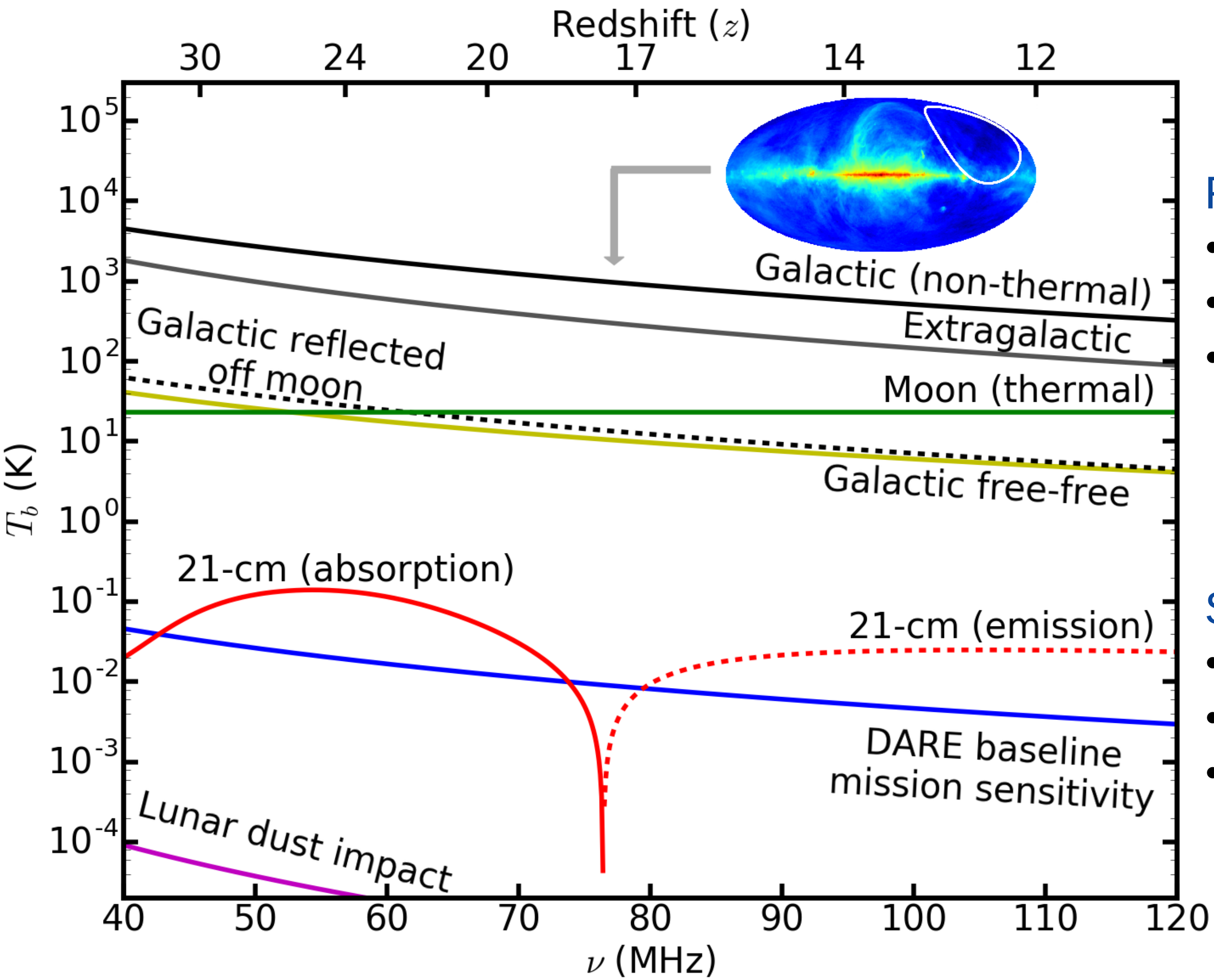
Collaborators:

- Michael Bicay, NASA Ames Research Center
- Abhirup Datta, University of Colorado Boulder
- Jonathan Pritchard, Imperial College
- Eric Switzer, NASA GSFC

Graduate Students:

- Bang Nhan, University of Colorado
- Keith Tauscher, University of Colorado

Foregrounds and Beam Chromaticity



$$T_{ant}(\nu) = \frac{\int_0^{2\pi}\int_0^{\pi/2} T_{sky}(\nu,\theta,\phi)F(\theta,\phi,\nu)\sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi/2} F(\theta,\phi,\nu)\sin\theta d\theta d\phi}$$

weighting by antenna beam introduces spectral structure in foreground (e.g., Bernardi *et al.* 2015, Mozdzen *et al.* 2016)

Foreground Characteristics

- Spectrally smooth
- Spatial structure
- Polarized

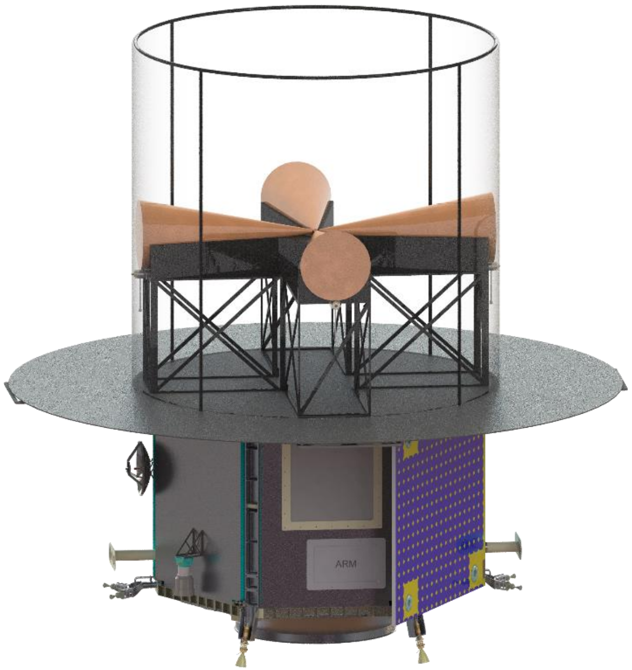
Signal Characteristics

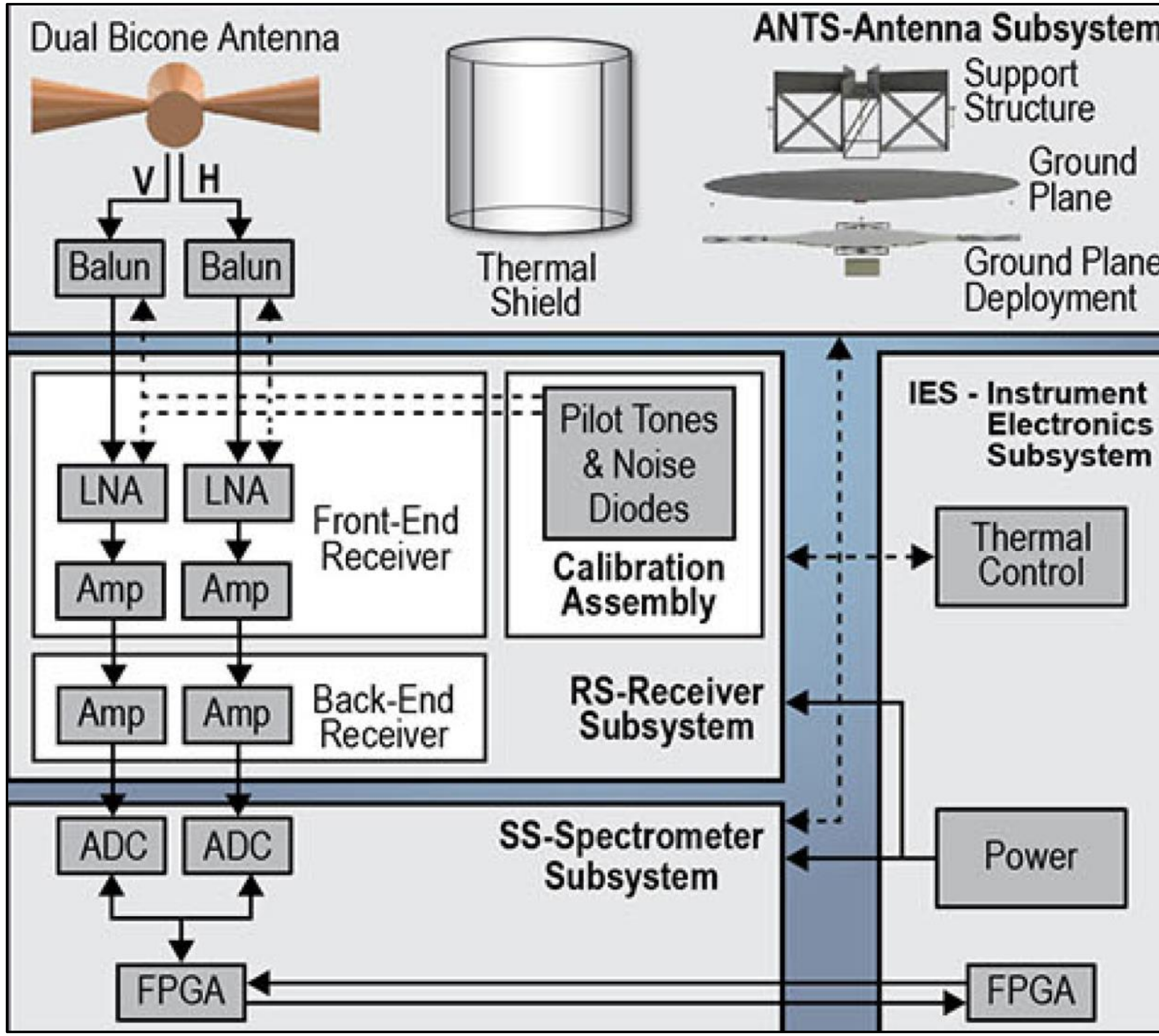
- Spectral structure
- Spatially isotropic
- Unpolarized

DARE Observatory

Two Year Mission Lifetime

- ~1000 hrs integration above lunar farside.
- shielded from Sun.
- 50x 125 km, equatorial orbit.



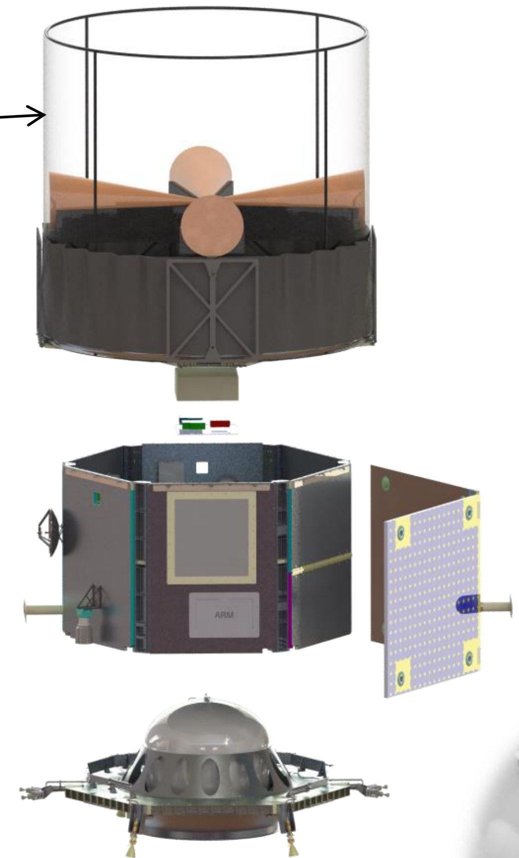


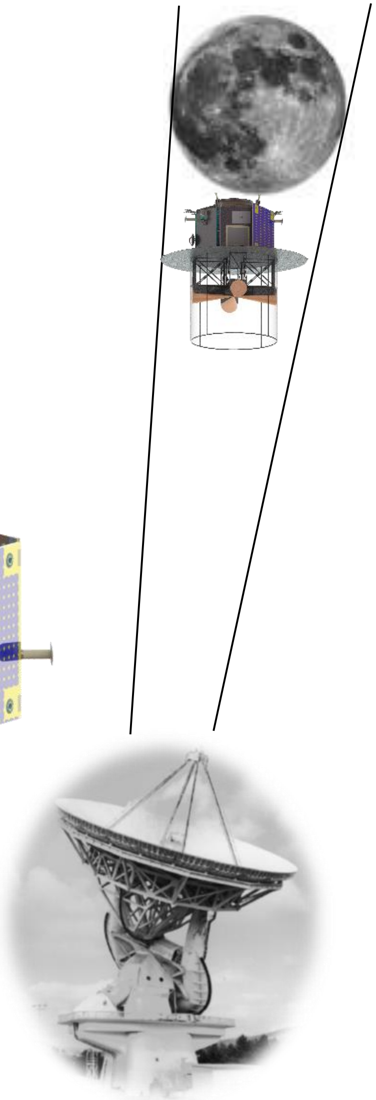
DARE probes z=11-35 with ν=40-120 MHz

DARK AGES RADIO EXPLORER

Chromaticity: Design Considerations

- Build antenna with low CTE material & minimize antenna thermal distortions (<10°C) with sunshade.
- Accurate modeling & measurement before launch.
- Measure beam on-orbit using frequency tones transmitted from Earth:
  - Circularly polarized, PSK modulated carriers (6) are sent from ground to DARE.
  - DARE receives signals as the spacecraft orbits above near side of the Moon to sweep beam.
  - Carrier levels are measured by DARE every 20 seconds to produce sampled beam cut.
  - A weak signal is also measured on its return trip to the Earth (Moon reflection) to estimate real-time path loss through the ionosphere.



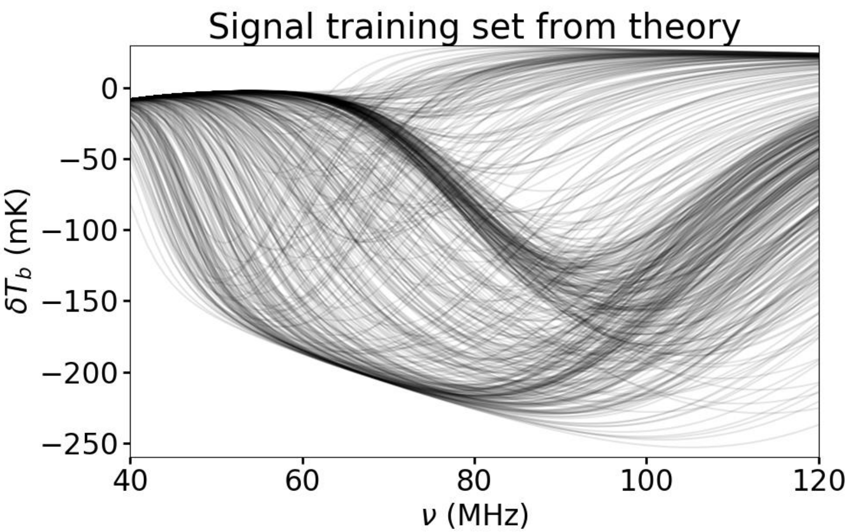


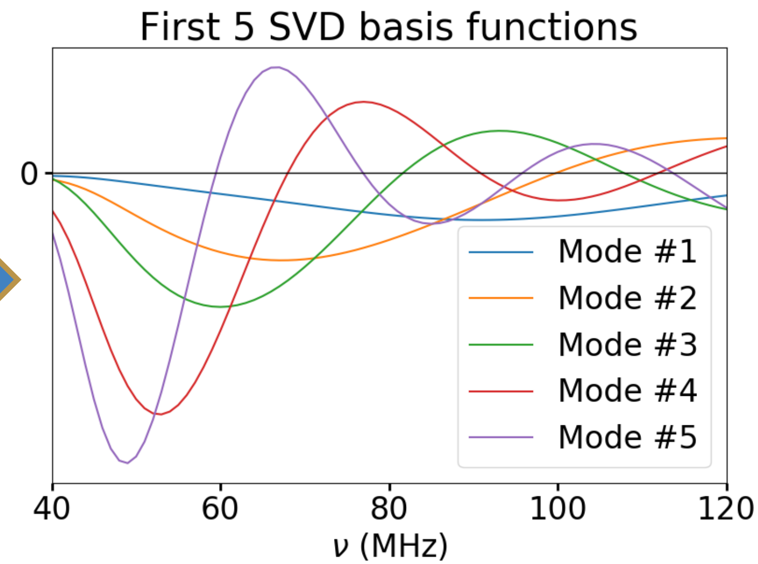
$$P_{echo} = \left(\frac{c^2}{64\pi^3}\right)\cdot\left(\frac{1}{\nu^2}\right)\cdot\left(\frac{P_t G_t^2 L_i^2 \sigma_m}{R_{t-M}^4}\right)$$ = echo power at 140-ft

Green Bank Observatory 140-ft antenna

DARE DARK AGES RADIO EXPLORER

Singular Value Decomposition (SVD) of Training Sets





Utility of SVD in easing requirements

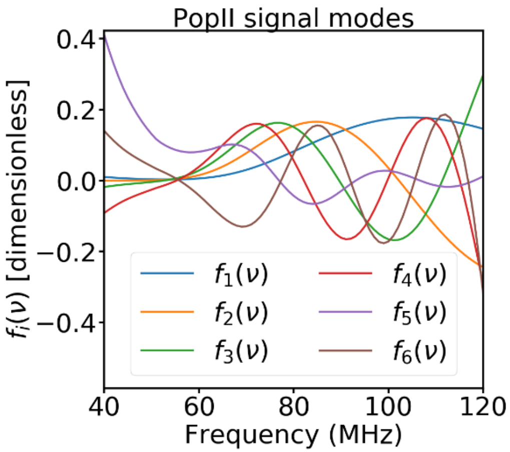
- SVD is a way of writing any matrix, M, as a matrix product:

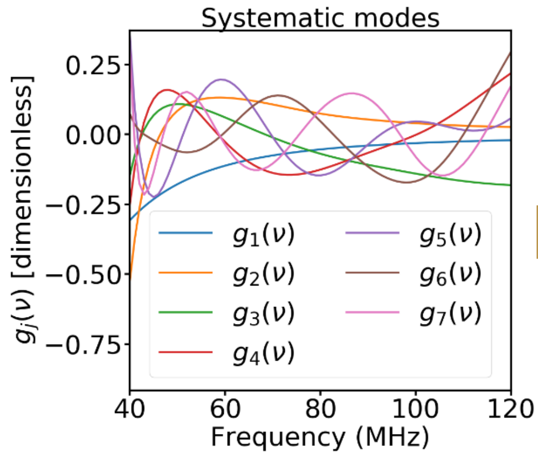
$$\underbrace{M}_{\substack{\text{Training Set:} \\ (N_{channel} \times N_{curves})}} = \underbrace{U}_{\substack{\text{Ordered basis functions:} \\ (N_{channel} \times N_{channel})}} \Sigma V^T$$

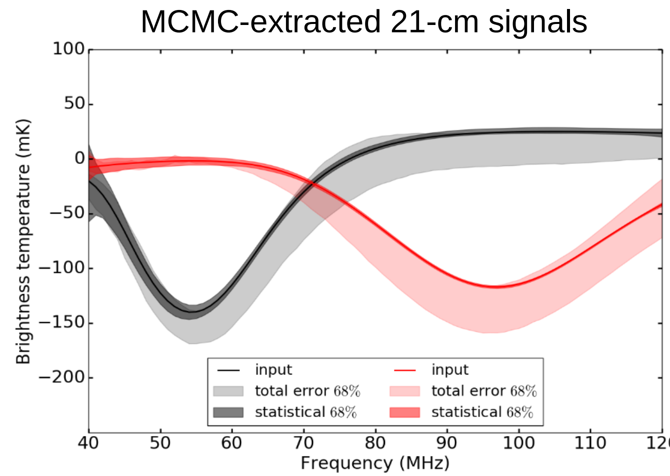
- SVD provides the optimal basis with which to fit the curves in a given training set.

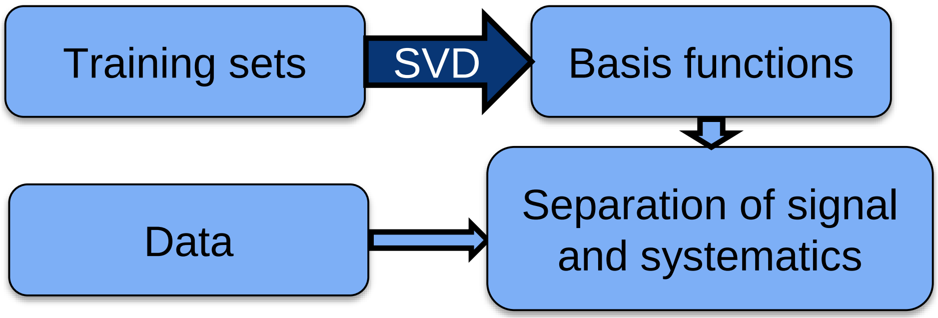
See also Switzer & Liu 2014, Paciga et al. 2013, Vedanthum et al. 2014

Training with Singular Value Decomposition (SVD)









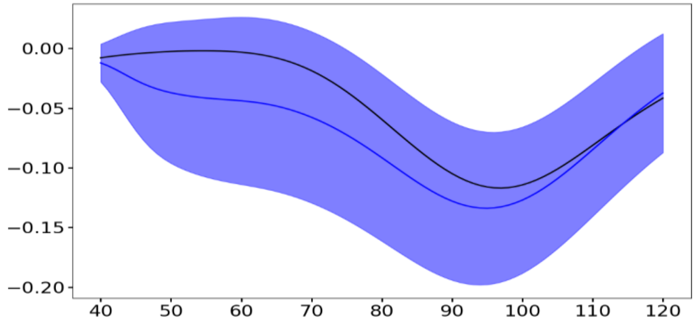
Utility of SVD in easing requirements

- By picking out the strongest modes of variation, SVD transforms the problem of separation from an absolute one into a relative one

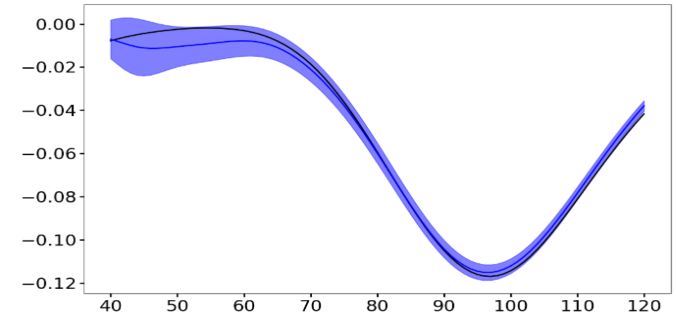
Burns et al. 2017; Tauscher et al. 2017 (in prep.); Rapetti et al. 2017 (in prep.)

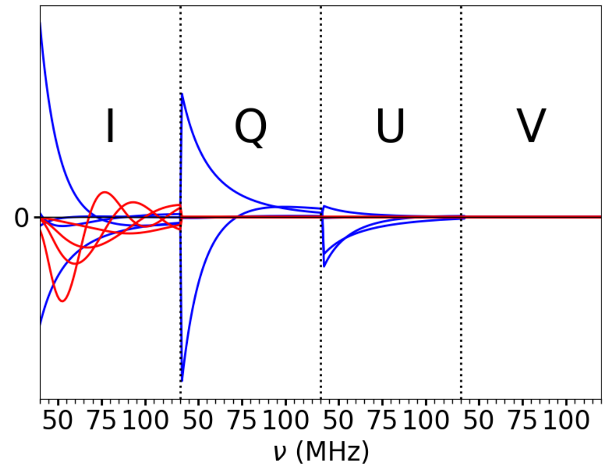
Separating systematics with induced polarization

No polarization data used



Polarization data used





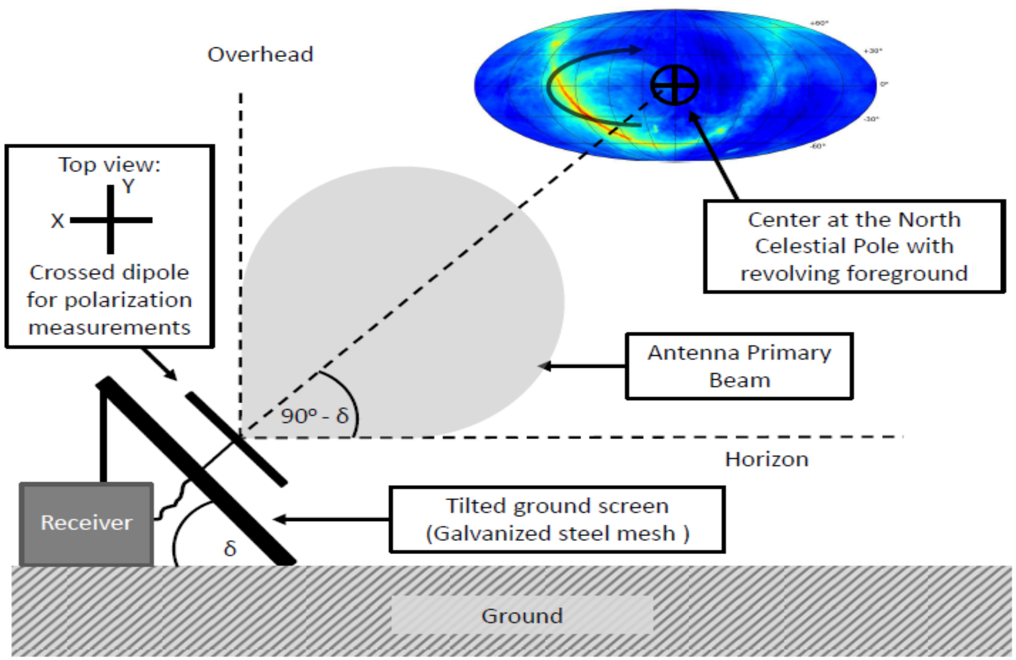
$$\ln L(\boldsymbol{\gamma}) = -\frac{1}{2}\sum_{\alpha\in\{I,Q,U,V\}}\sum_{\phi}\sum_{r}\sum_{\nu}\left[\frac{S_\alpha^{(r,\phi)}(\nu)-\mathcal{M}_\alpha^{(r,\phi)}(\boldsymbol{\gamma};\nu)}{\sigma_\alpha^{(r,\phi)}(\nu)}\right]^2$$

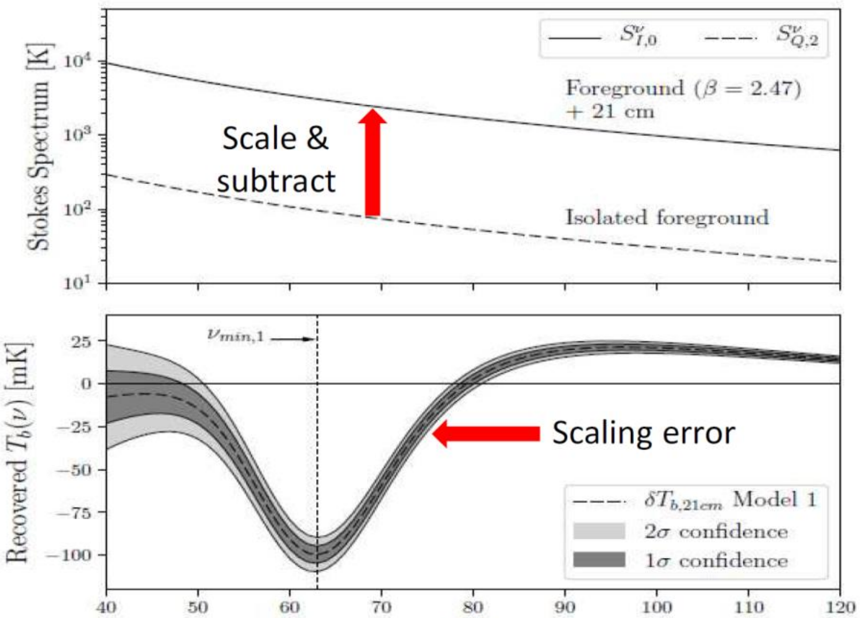
Likelihood function

$$\mathcal{M}_\alpha^{(r,\phi)}(\boldsymbol{\gamma};\nu) = \sum_k f_{\alpha,k}^{(r,\phi)}(\nu)+\delta_{\alpha I}\,B^{(r,\phi)}(\nu)\,\sum_j g_j(\nu)$$

Prototype: Cosmic Twilight Polarimeter

Collaboration between NRAO & University of Colorado





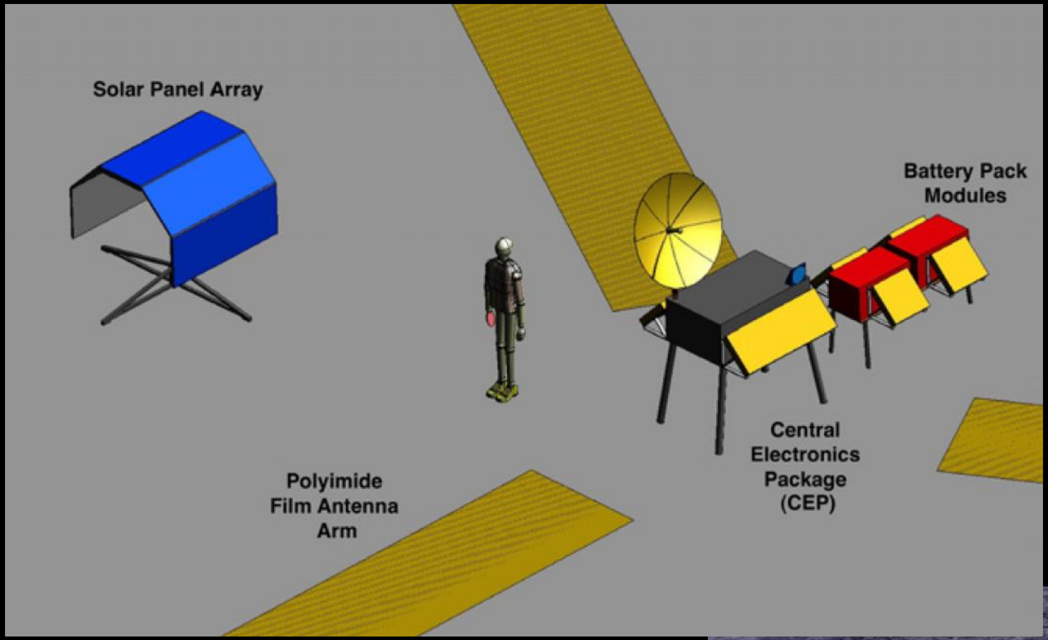
Nhan et al. (2016)

Polarimetry Process to measure Foreground

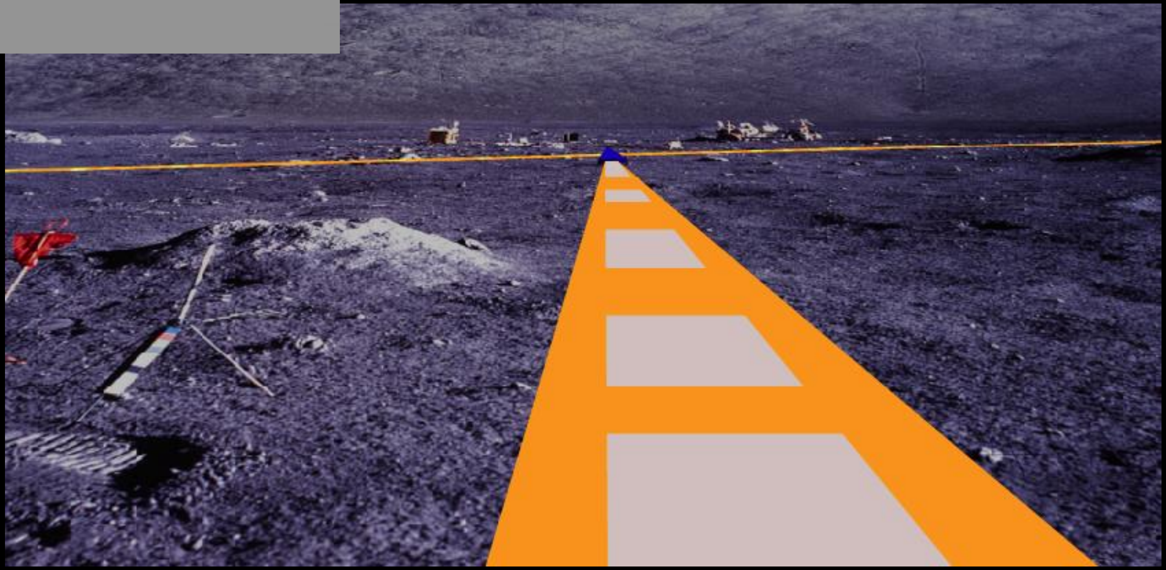
1. Measure "polarization leakage" caused by ν-dependence of power patterns of linearly polarized dipoles. Rotation of sky to measure modulated Stokes Q, U, V.
2. Harmonic decomposition of modulated Q, U signal, scale to Stokes I, and subtract.

Nhan, Bradley, & Burns, 2017, ApJ, 836, 90.

Toward a *Cosmic Dawn Mapper*



Lazio, MacDowall, Burns *et al.*, 2011, *Advances in Space Research,* 48, 1942

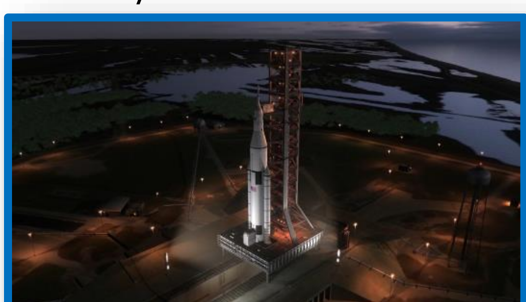


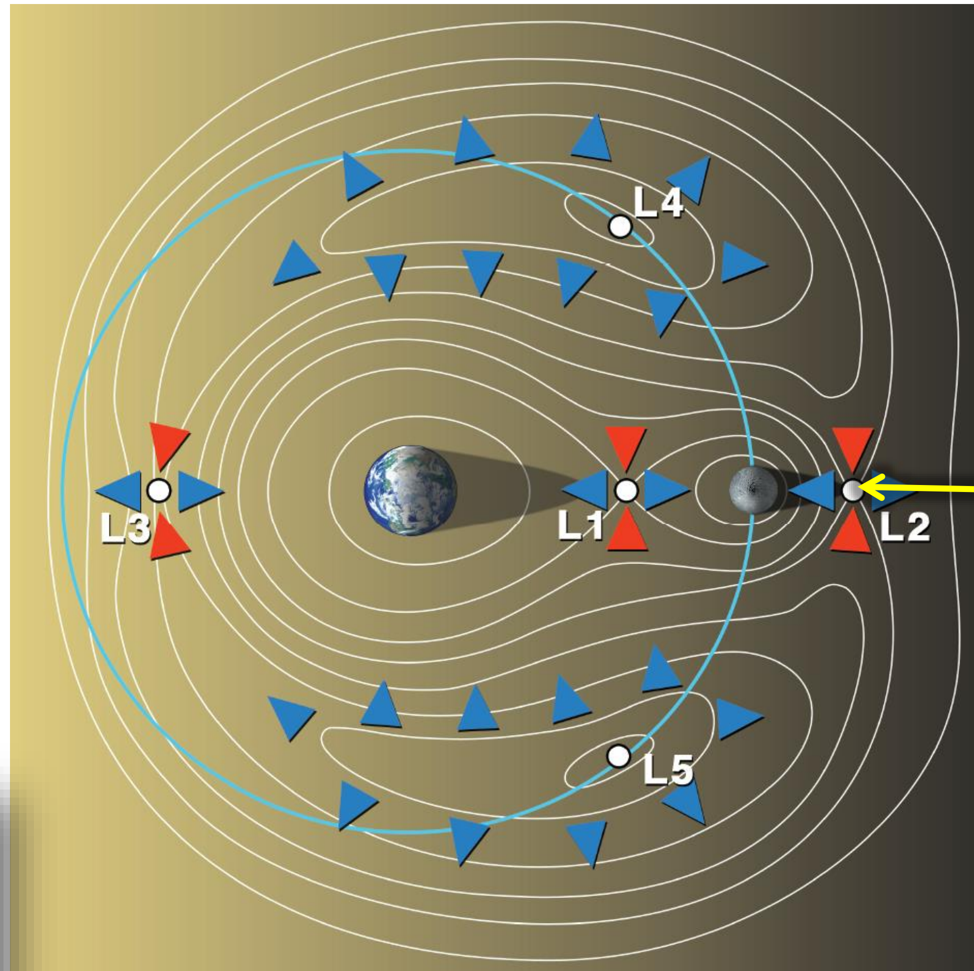
Network for Exploration and Space Science

Deep Space Gateway at Earth-Moon L2 can deploy a low frequency telescope on farside via teleoperated rover

- E-M L2 is 60,000 km above farside. Minimal station-keeping to orbit about L2.
- First uncrewed mission is 2019 & first crewed mission is ~2021.

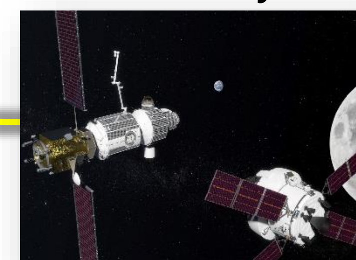
Orion/SLS – NASA video

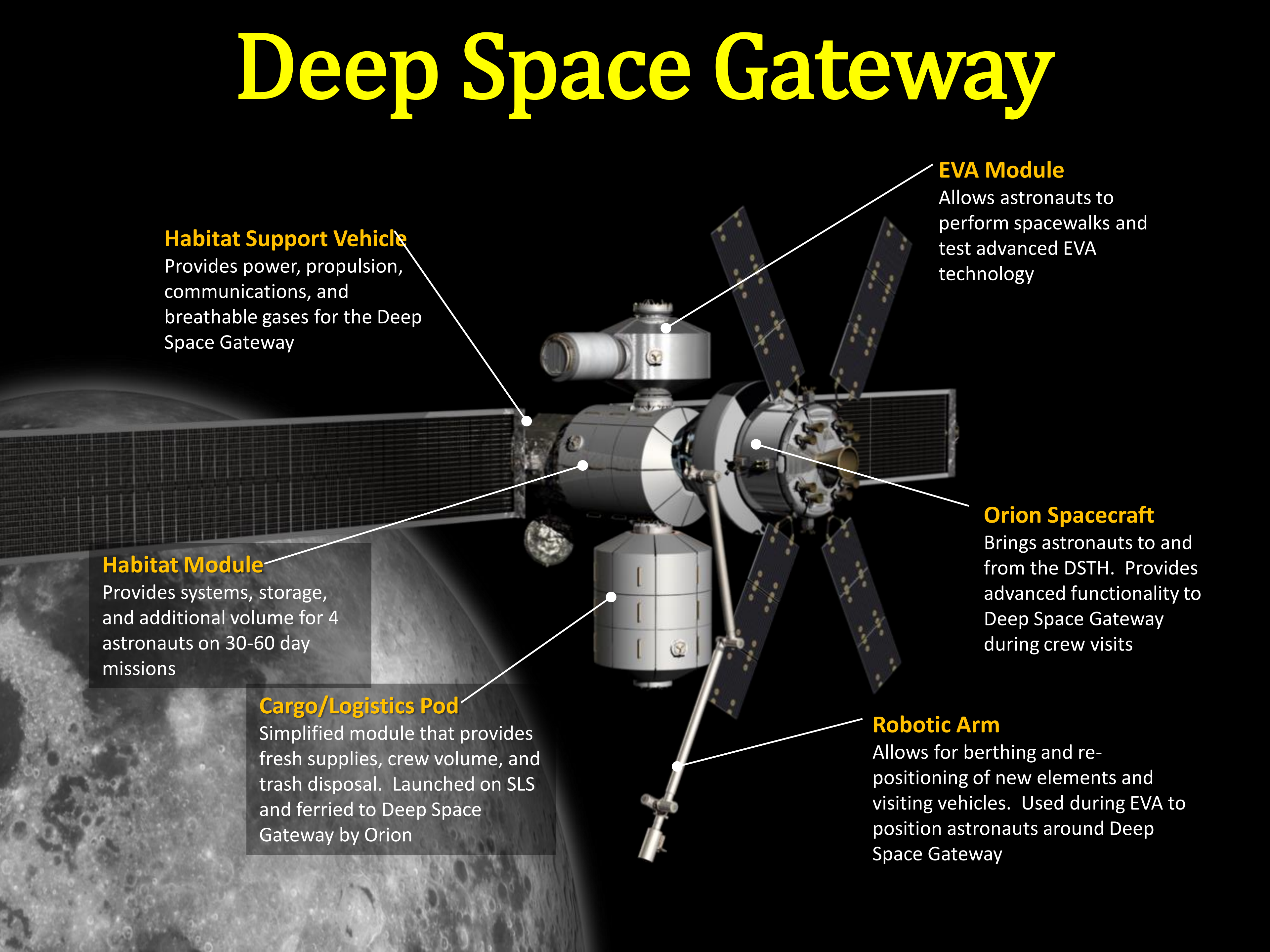




Lagrange points in cis-lunar space

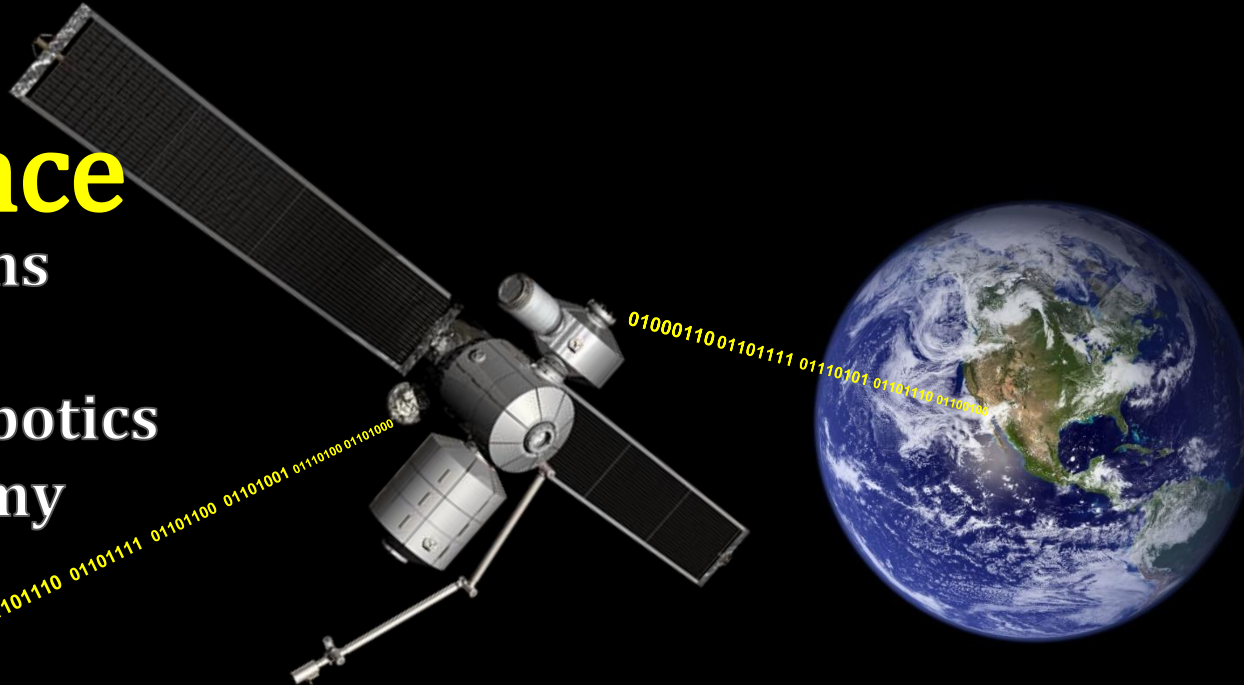
Gateway




Deep Space Gateway
EVA Module
Allows astronauts to perform spacewalks and test advanced EVA technology
Habitat Support Vehicle
Provides power, propulsion, communications, and breathable gases for the Deep Space Gateway
Orion Spacecraft
Brings astronauts to and from the DSTH. Provides advanced functionality to Deep Space Gateway during crew visits
Habitat Module
Provides systems, storage, and additional volume for 4 astronauts on 30-60 day missions
Cargo/Logistics Pod
Simplified module that provides fresh supplies, crew volume, and trash disposal. Launched on SLS and ferried to Deep Space Gateway by Orion
Robotic Arm
Allows for berthing and re-positioning of new elements and visiting vehicles. Used during EVA to position astronauts around Deep Space Gateway

Lunar Science

- Communications Relay
- Surface Telerobotics
- Radio Astronomy
- Radiation
- Sample Return



Rover Image
Courtesy MDA

NESS Telerobotic Deployment
Burns et al. (2013)

Lander Graphic
Courtesy JPL

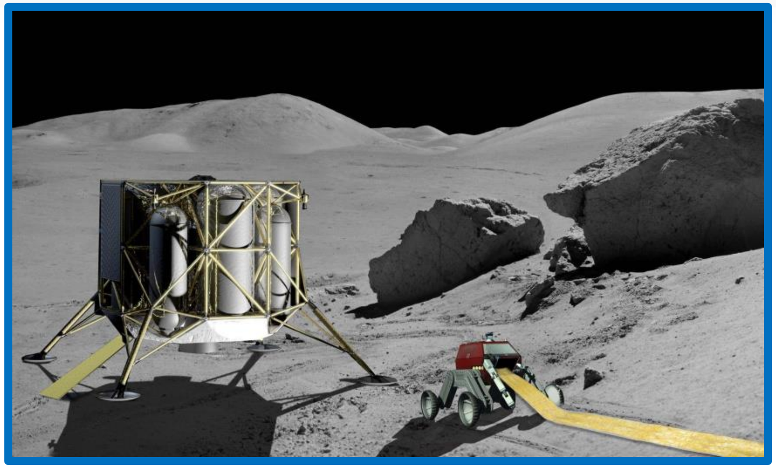
NESS
Network for Exploration and Space Science

Telerobotic Deployment of a Lunar Radio Array

NESS
Network for Exploration and Space Science

Astronaut Luca Parmitano (Italy) orbiting Earth on the ISS teleoperates the K10 rover at NASA Ames to simulate deploying a lunar farside radio telescope.

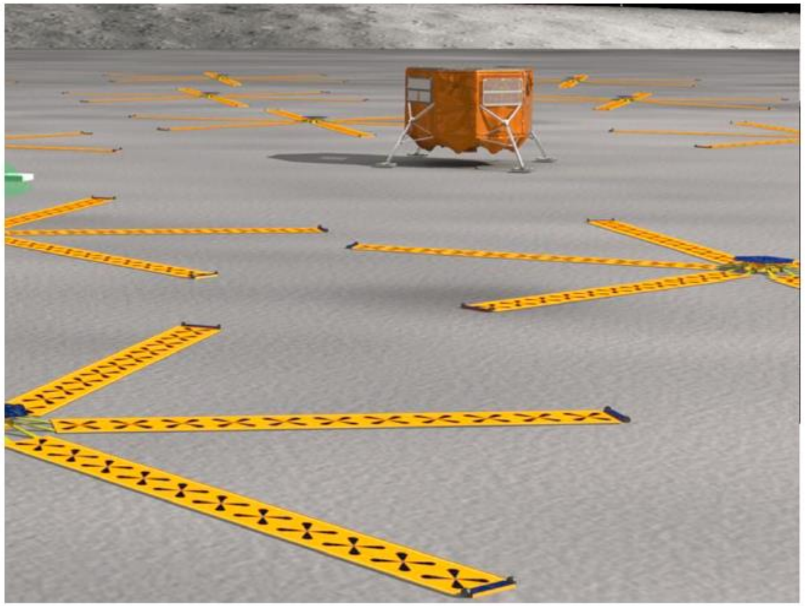
Burns, Fong, Kring et al. 2017, *IAA Symposium on Space Exploration*, arXiv:1705.09692.



Burns *et al.* 2013, *Ad. Space Res.*, 52, 306.

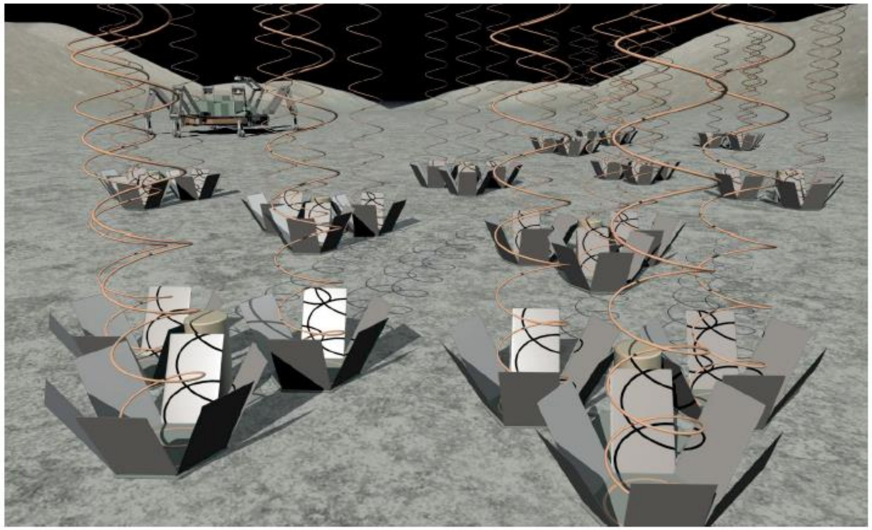
Previous Studies (circa 2009)

DALI/ROLSS
(Lazio et al.)



- Dipoles (1x1 m) on Kapton
- 1500 dipoles/station
- DALI: 300 stations
- ROLSS: 1 station

LARC Cosmic Dawn Array
(Hewitt et al.)



- Helical stances: 1.2 x 8.2 meters
- 10,000 stances

Ballpark numbers

At 10 MHz:

- 1 degree resolution requires ~2 km baselines
  - Filled aperture: 1 element / 3600sq. m
  - Circle layout: 1 element / 6 meters
- 10^5 square meters collecting area requires >1000 dipoles
- 1000 dipoles * 2 pol * 20 MHz bandwidth → ~40 GB/s

- Power
  - Analog: 1000 dipoles * 0.1W = 200 W
  - Channelization: 2000 channels * 10W/32channels (FPGA) = 600W
  - Correlation: Currently ~5 GPU servers * 500W = 2500W
  - Can likely reduce by order of magnitude with ASICs, etc.
    - LARC estimated 200W using GeoSTAR correlator

Lunar Prototype Array Trade Study

Network for Exploration and Space Science

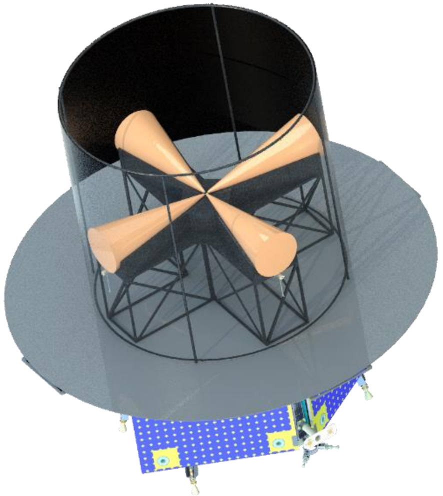
- Literature review (Summer 2017)
  - Previous design/trade studies (LARC, ROLSS, etc.)
  - Relevant technologies, TRLs, etc.
  - Lunar conditions
    - RFI, regolith properties, environment, dust, radiation, etc.

- Science objective definition (Fall 2017)
  - "Notional" full-scale science objectives
    - Exoplanet space weather, 21cm cosmic dawn, heliophysics, etc.
    - Total collecting area, observation band, angular resolution, etc.
  - Select subset of science scoped to a small prototype array

- Trade study of design options for prototype array (Spring 2018) - Goal to identify reference prototype design and key technology development
    - Antenna design, polarization, etc.
    - Array configuration, collecting area
    - Location on lunar surface
    - Operational model (lunar day/night, duty-cycle, etc.)
    - Processing, data rate, data volume, etc.
    - Deployment methods
    - Mass, power, cost
    - End-to-end system (communications requirements/relays, power sources/storage, etc.)

Summary and Conclusions

- The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environs at z>10.
- *DARE science instrument*: biconical dipole antenna, pilot-tone injection receiver, digital spectrometer, polarimeter, & SVD MCMC signal extraction pipeline.
- Prototype low frequency antennas and arrays on the lunar surface may be viable in the mid-2020's via telerobotic deployment from NASA's Deep Space Gateway.
- NASA-funded Trade and Science Definition studies for lunar farside arrays are underway now to prepare for deployment in the mid to late 2020's.



Supplemental Slides

NESS

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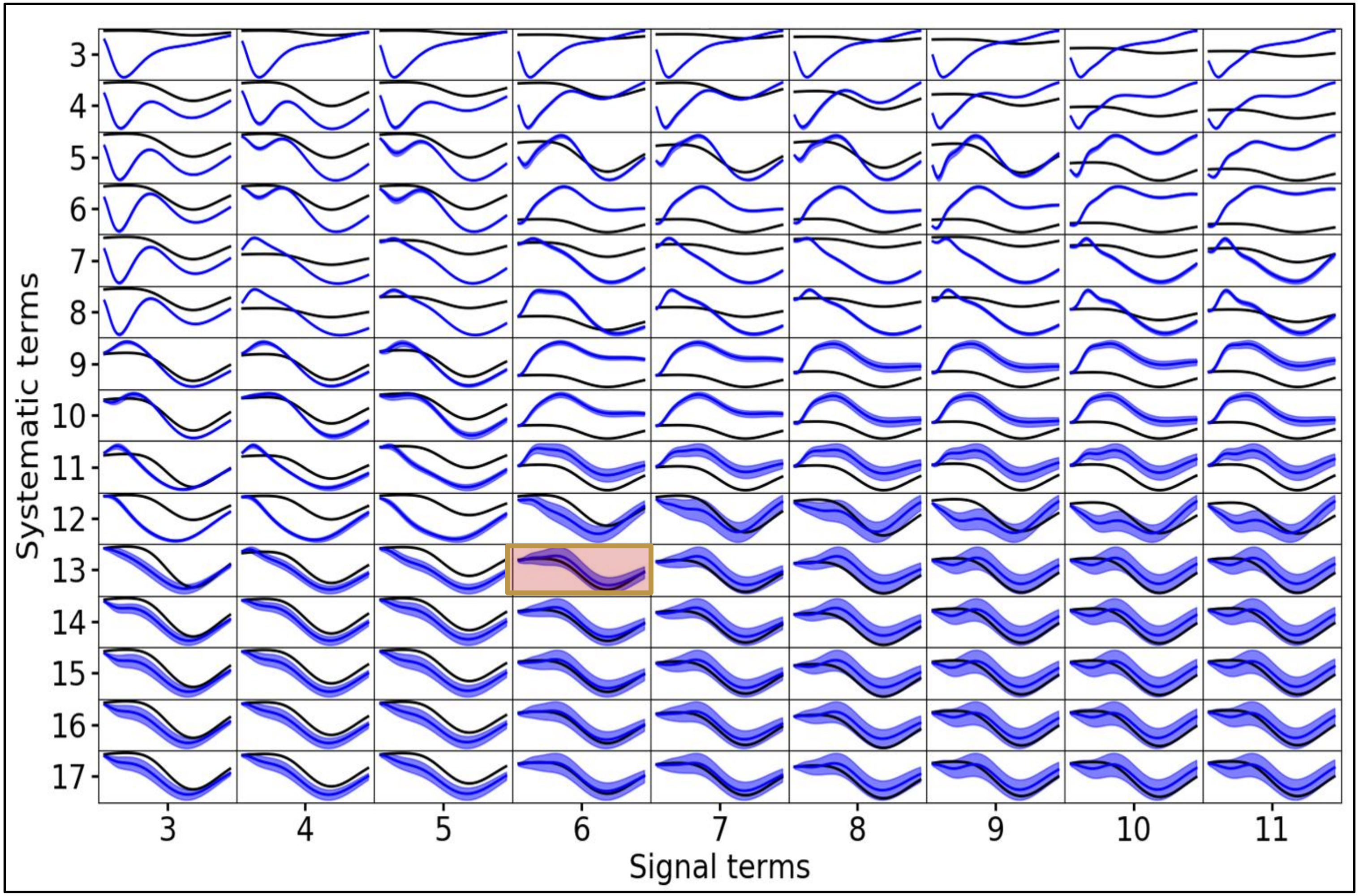
Optimizing Signal Extraction



We use the ***BPIC (Bayesian Predictive Information Criterion)*** statistic to blindly select a model with the number of SVD modes necessary to fit the data. The chosen model (red rectangle) has the minimum BPIC.