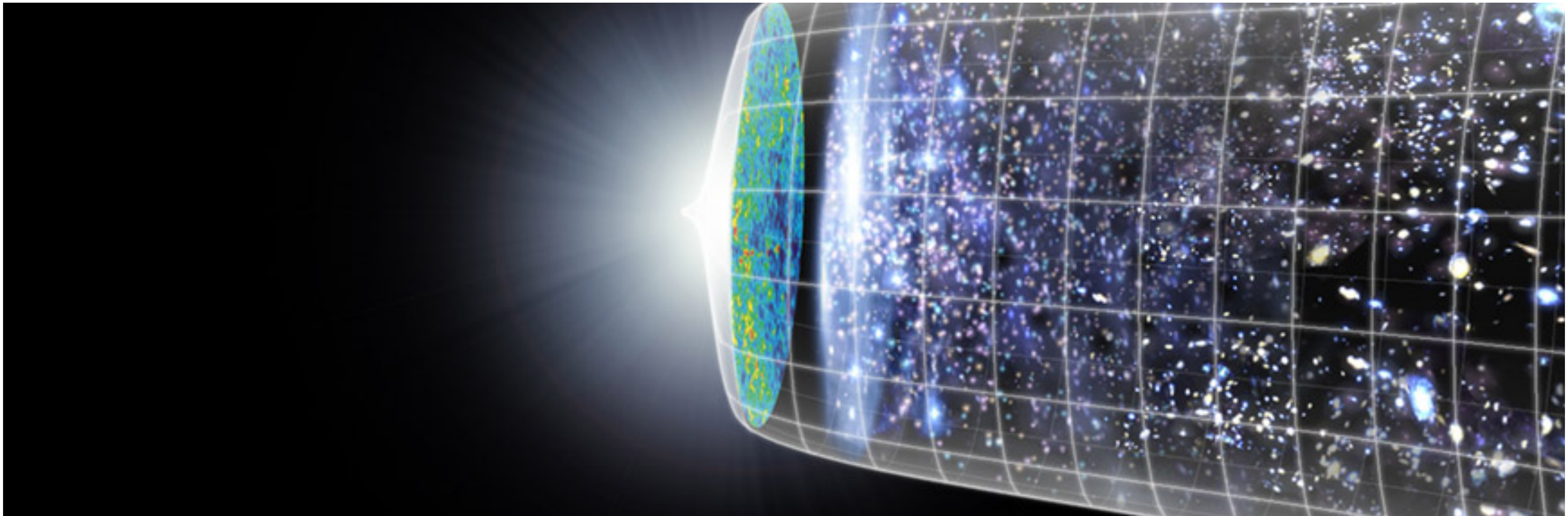
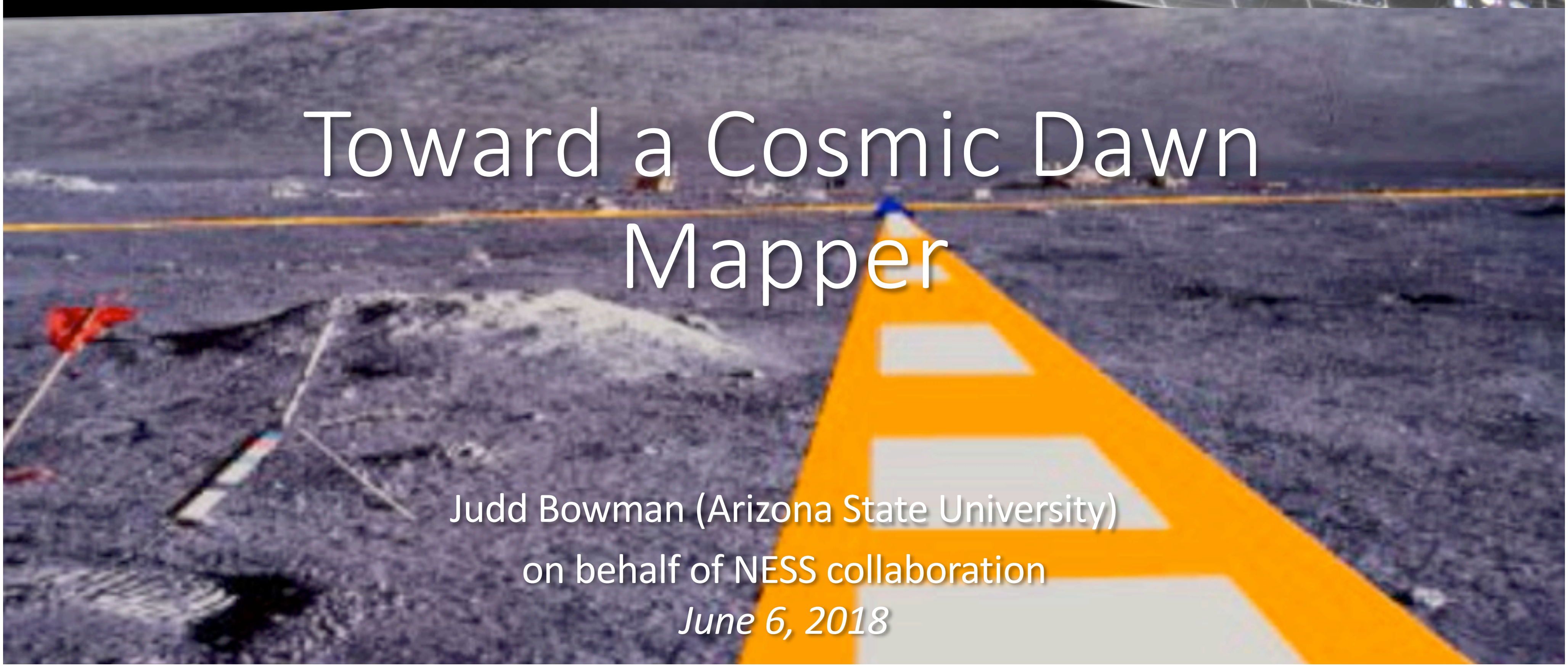




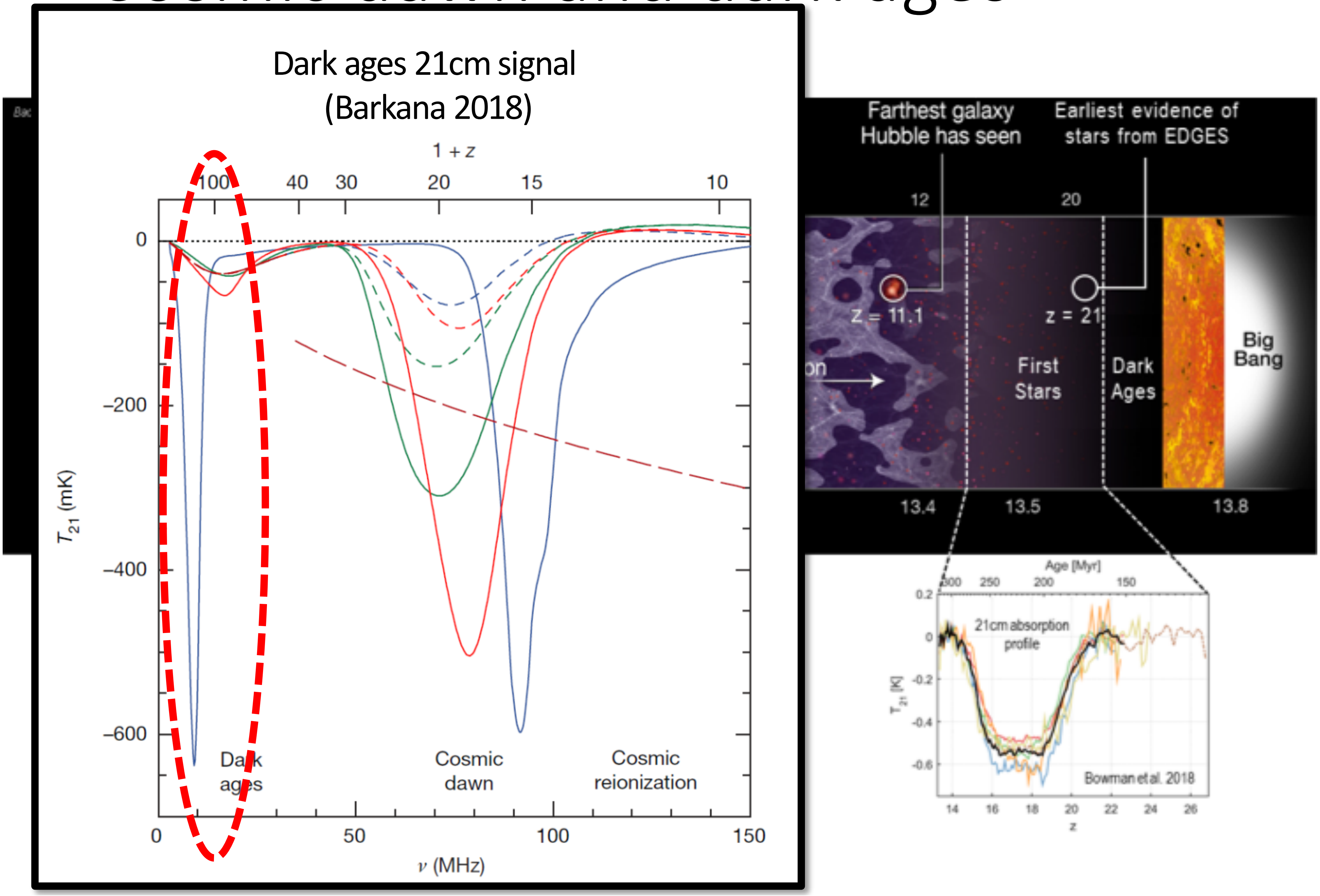
Toward a Cosmic Dawn Mapper

Judd Bowman (Arizona State University)

on behalf of NESS collaboration

June 6, 2018

Cosmic dawn and dark ages



Why the Moon

- Earth's ionosphere absorbs astronomical radio emission below 200 MHz and blocks it below ~20 MHz
  - Perturbations in ionosphere lead to distortions and scintillations
- Lunar farside is shielded from Earth transmitters and Earth auroral emission (AKR)
- Lunar surface advantages:
  - Fixed antennas require no propulsion to maintain
  - Simpler operations, data transportation
- Lunar orbit advantages:
  - No landing on surface (fuel, mass, cost)
- NASA's Deep Space Gateway could enable:
  - Communications hub and relay
  - Power source for data processing if at DSG
  - Possibly beam power to array for lunar night operation/survival
  - Teleoperated robotic deployment of array antennas

Cosmic dawn array

Science Traceability Matrix			
Decadal Science Goals	**Science Objectives**	**Science Measurements**	**Instrument Requirements**
1) How do structures form and evolve? 2) How do stars form? 3) What is the fossil record of galaxy assembly from the first stars to the present?	1) What are the properties of early stars and galaxies and their environments? i.e. What is the average star formation efficiency, ionizing efficiency, X-ray efficiency, minimum virial temperature for formation, etc. for early galaxies?	1) Power spectrum of redshifted 21cm absorption fluctuations during cosmic dawn 2) Frequency range approx. 60-95 MHz ($15<z<25$) 3) Angular modes between 1 and 10 degrees 4) Spectral modes between 0.05 to 4 MHz	1) Full Stokes aperture synthesis array on lunar farside (surface or orbit) to avoid ionosphere and RFI 2) Radio receivers, timing system, etc., to provide data for synthesis 3) High-precision bandpass and beam calibration for foreground removal 4) Hardware that is radiation and thermally tolerant to survive the lunar environment 5) Deployer for chosen antenna design
4) What are the connections between dark and luminous matter?	2) Did interactions between dark matter and baryons cool the early IGM?		

Dark ages array

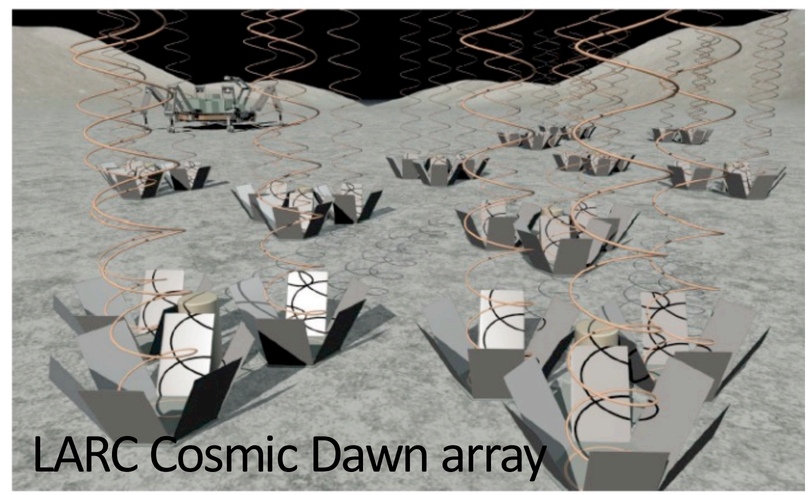
Science Traceability Matrix			
Decadal Science Goals	**Science Objectives**	**Science Measurements**	**Instrument Requirements**
1) What is the nature of inflation?	1) Are primordial matter density perturbations non-Gaussian? What is the value of f_{NL}?	1) Power spectrum of redshifted 21cm absorption fluctuations before stars 2) Frequency range approx. 10-40 MHz $(50<z<100)$ 3) Angular modes between 1 and 10 degrees 4) Spectral modes between 0.05 to 4 MHz	1) Full Stokes aperture synthesis array on lunar farside (surface or orbit) to avoid ionosphere and RFI 2) Radio receivers, timing system, etc., to provide data for synthesis 3) High-precision bandpass and beam calibration for foreground removal 4) Hardware that is radiation and thermally tolerant to survive the lunar environment 5) Deployer for chosen antenna design
	2) What are the cosmological parameter values?		
2) What is the nature of dark matter?	3) What is the temperature evolution of baryons after recombination?		

Collecting area

- 21cm fluctuations are ~0.01 K
  - 1,000,000 independent samples in observation
  - Minimum SNR=10 on power spectrum requires <10 K noise per pixel
- Foregrounds (and noise) go as ~250 $(\nu/150\ \mathrm{MHz})^{-2.5}$ K
  - 75 MHz: 1500 K
  - 30 MHz: 15,000 K
- Minimum time to reach SNR=10 for a filled aperture:
  - 75 MHz: 31 hours (1 week)
  - 30 MHz: 3100 hours (1 year)
- Collecting area of filled aperture for 1° angular resolution:
  - 75 MHz: 65,000 m^2 → ~10,000 dipole-like antennas
  - 30 MHz: 400,000 m^2 → ~10,000 dipole-like antennas

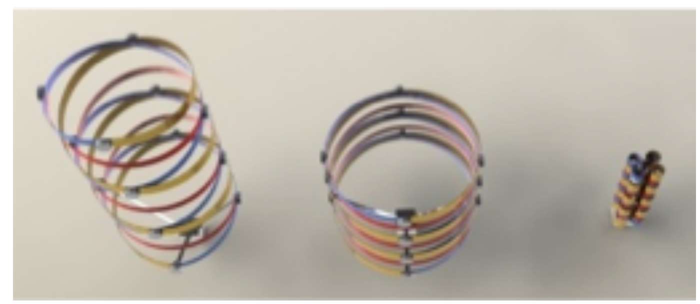
Notational dark ages array from requirements

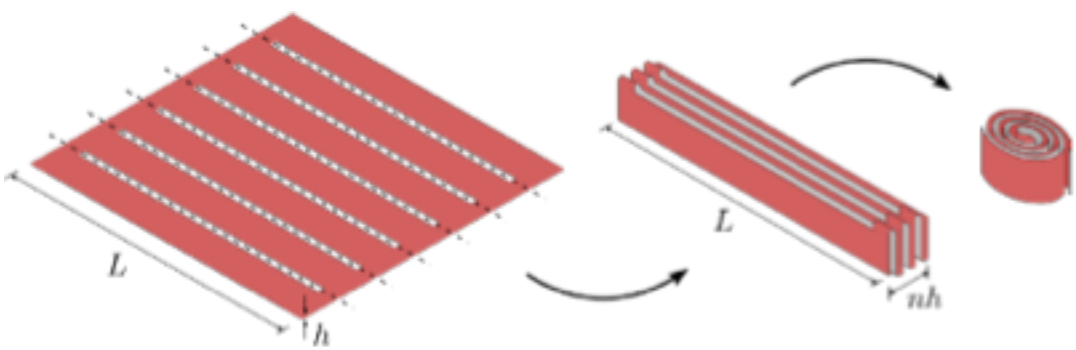
- Location:
  - Lunar farside
- Antennas:
  - Dual polarization for full Stokes
  - Probably higher-gain than dipole
- Frequency band:
  - 10-40 MHz
- 10 K sensitivity per pixel:
  - 10,000 antennas (if dipole-like)
- 1 degree resolution:
  - ~1 km baselines
- Data rate: 300 GB/s (raw)
- Power estimate:
  - Analog 10,000 elements: ~2 kW
  - Digital processing: ~10 kW
- Lifetime:
  - 5-10 years



Key technology - antennas

- Plausible total (packed) array mass, volume:
  - ~10,000 kg
  - ~10 m^3
- Hence, need extremely low mass and low volume per antenna
  - 1 kg
  - 1000 cm^3
  - e.g. 1U cubesat: (10x10x10 cm)





Space Structures Lab (Caltech)

Multi-Science Pathfinder Array Trade Study

Judd Bowman, Gregg Hallinan, Robert MacDowall

NESS collaboration

Pathfinder top-level science goals

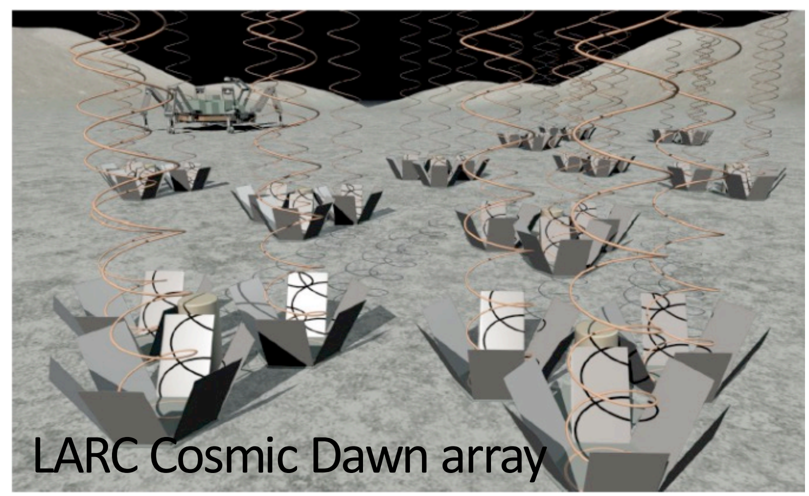
- **Cosmology: What are the foregrounds for 21cm dark ages?**
  - Create spectral data cubes of diffuse emission
  - Maps of radio recombination lines
- **Exoplanets: What is the habitability of exoplanets?**
  - Flares and CME events severely impact the ability of planets to retain their atmospheres.
  - Characterize statistics of stellar flares to improve estimates of habitability.
    - Comparative study of burst statistics of two stellar systems, one sun-like and one M-dwarf.
    - Detect and resolve stellar bursts from **Alpha Centauri (A and B)** and **Proxima Centauri**
  - Monitor hundreds of other M-dwarfs for stellar flares
- **Heliophysics: How are energetic particles accelerated in solar bursts?**
  - Determine where and how the radiating particles are accelerated by imaging Type II and Type III solar radio bursts.
  - Monitor CMEs to improve space weather forecasting.

Combined science to instrument properties

		Science goals		
		Heliophysics	**Exoplanet habitability**	**21cm Dark ages foregrounds**
Instrument property	**Frequency range**	1-10 MHz	<20 MHz (stellar bursts and Jovian-type emission)	<40 MHz
	Spectral resolution	1%	10%	10 kHz (RRLs)
	Field of view	>10 deg (all-sky for CME monitoring)	the larger the better to capture occasional 1000-fold increases in planetary radio power	the larger the better to map more of sky
	Angular resolution	2 degrees	2 degrees	1 degree
	Sensitivity	10^4 Jy	1 Jy for stellar bursts (Earth is 1 mJy at 5pc when geomagnetic storm)	1000 K
	Observing requirements	Sun and ecliptic visible	far side because of contamination from RFI and AKR, southern hemisphere	far side because of RFI
	Polarization	full Stokes for science	full Stokes -- high fidelity Stokes V imaging required for science	full Stokes for foregrounds

Pathfinder array – 1% collecting area

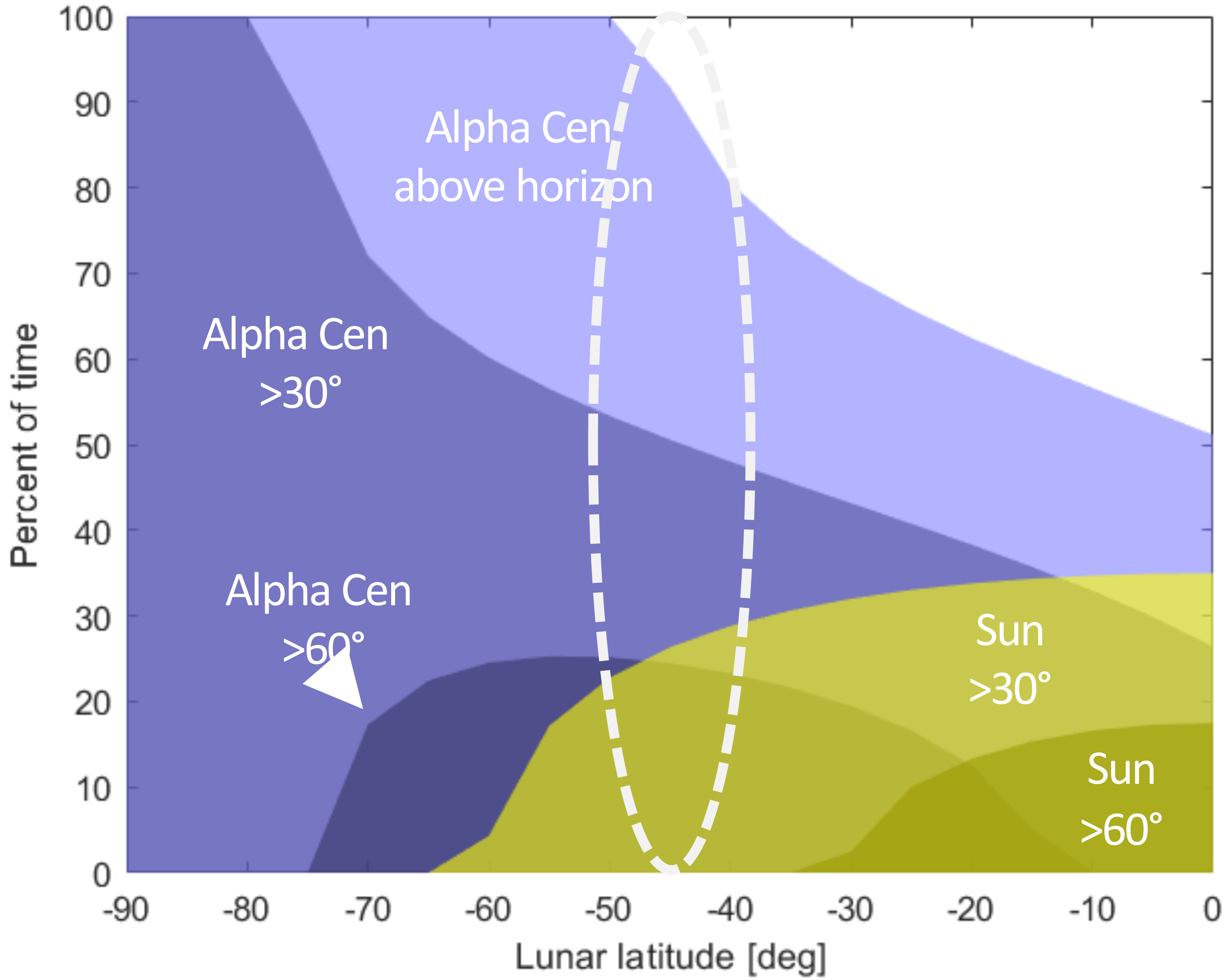
- Lunar farside
- Frequency band:
  - 1-20 MHz
- 1 Jy sensitivity:
  - 100 dipole-like antennas
- 1 degree resolution:
  - 1 km baselines
- Data rate:
  - 4 GB/s (raw)
- Power estimate:
  - Analog 100 elements: <20 W
  - Digital processing: 10-100 W
- Lifetime:
  - 1-5 years
- Mass and volume:
  - Relax by order of magnitude
  - 10^4 cm^3 per antenna = 1 m^3 total
  - 10 kg per antenna = 1000 kg total



Pathfinder array trade space

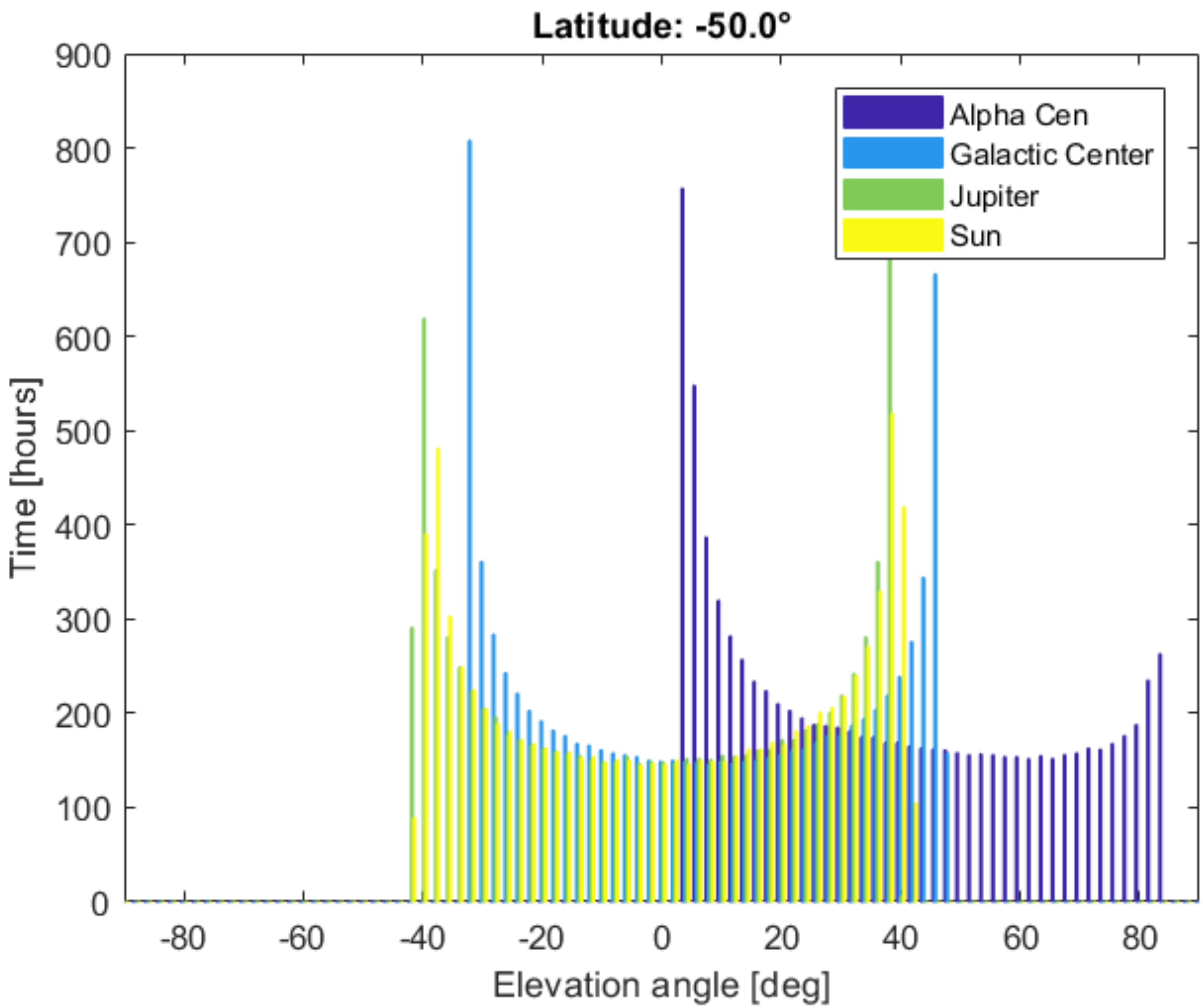
- Array location:
  - RFI attenuation
  - Science target visibility
  - Data/communications
- Array layout:
  - Imaging performance
- Antenna design:
  - Planar dipoles directly deployed on regolith (no ground plane)
  - Dipole-like antennas with ground planes
  - 3D (e.g. helical) antennas
  - Metrics: mass, volume, deployment complexity
- Data transportation from antennas:
  - Copper, fiber, microwave, optical, analog vs. digital
  - Primary metrics: power, data quality, deployment complexity
- Deployment methods
  - Direct land each antenna
  - Deploy antennas printed on polyimide rolls
  - Deploy antennas by rover (fixed or deployable)

Pathfinder array location



- Metric: amount of time sun and Alpha/Proxima Cen (dec. −61°) are visible
- Result: mid-latitude southern hemisphere

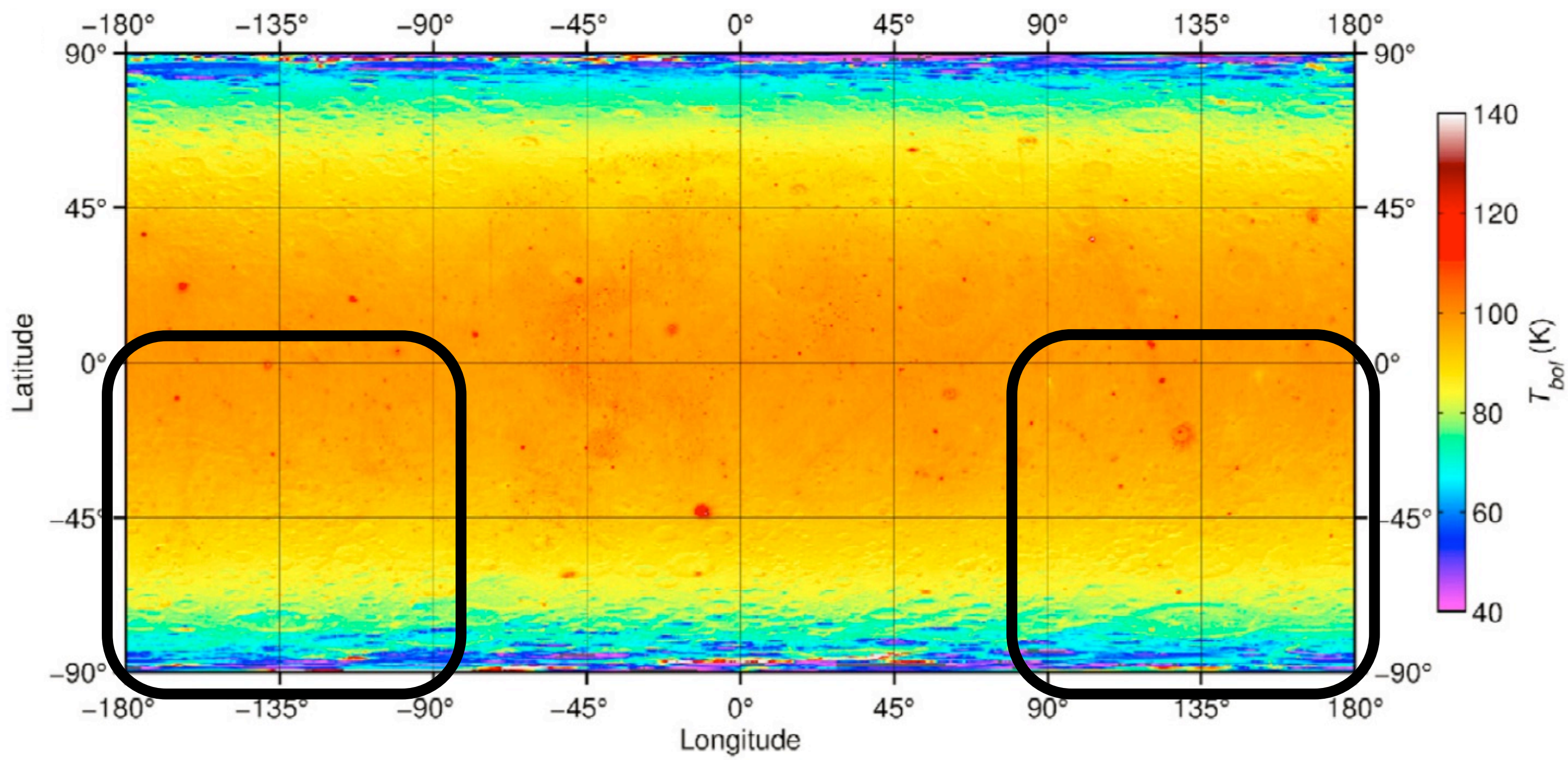
Pathfinder array location



- Motivates low-gain antennas because targets move through entire sky

Mean low lunar temperatures

- At -45° latitude, minimum is ~90 K (high temps are 300-350 K)
- Warmest places are young craters with rocks (~5 K warmer)
- Diurnal variations extend to ~30 cm below surface
- Currently investigating candidate sites



LRO Diviner / Williams et al. 2017

Summary

- Dark ages lunar array would provide unique cosmology, but requires many antennas for adequate sensitivity
  - Primordial non-Gaussianity
  - Baryon thermal history
- Key technology development needed:
  - Radiation and temperature tolerant electronics and system designs
  - Low mass, low volume antennas
  - Antenna deployment
- Start with pathfinder lunar array
  - Immediate scientific benefit on the high-priority science of exoplanet habitability and solar shock acceleration
  - Crucial experience and investigation of the environmental and technical challenges
  - Trade study in progress, except initial results early 2019