A LUNAR FARSIDE LOW RADIO FREQUENCY ARRAY FOR DARK AGES 21-CM COSMOLOGY

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on behalf of the *FARSIDE* & *FarView* teams

APS B21: *Physics of the Cosmos & PhysPAG Town Hall*

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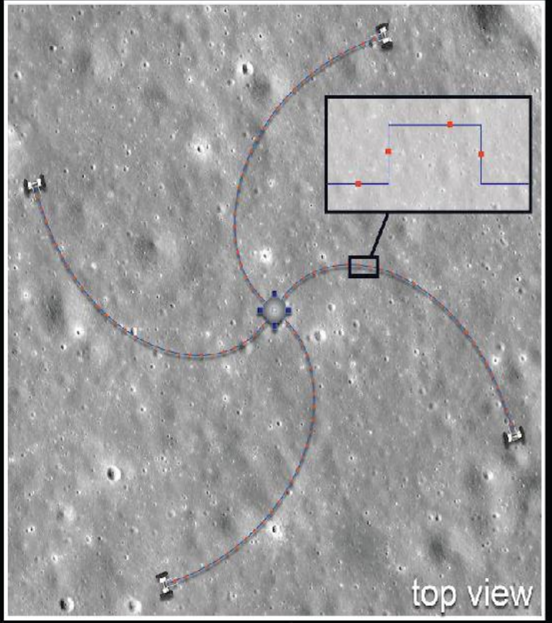
Network for Exploration and Space Science

Burns J.O., Hallinan, G., Chang, T-C et al. 2021, *A Lunar Farside Low Radio Frequency Array for Dark Ages 21-cm Cosmology*, NASA/DOE RFI whitepaper, arXiv:2103.08623.

Complete List of Authors for NASA/DOE RFI Whitepaper on a FARSIDE Radio Array for Dark Ages Cosmology



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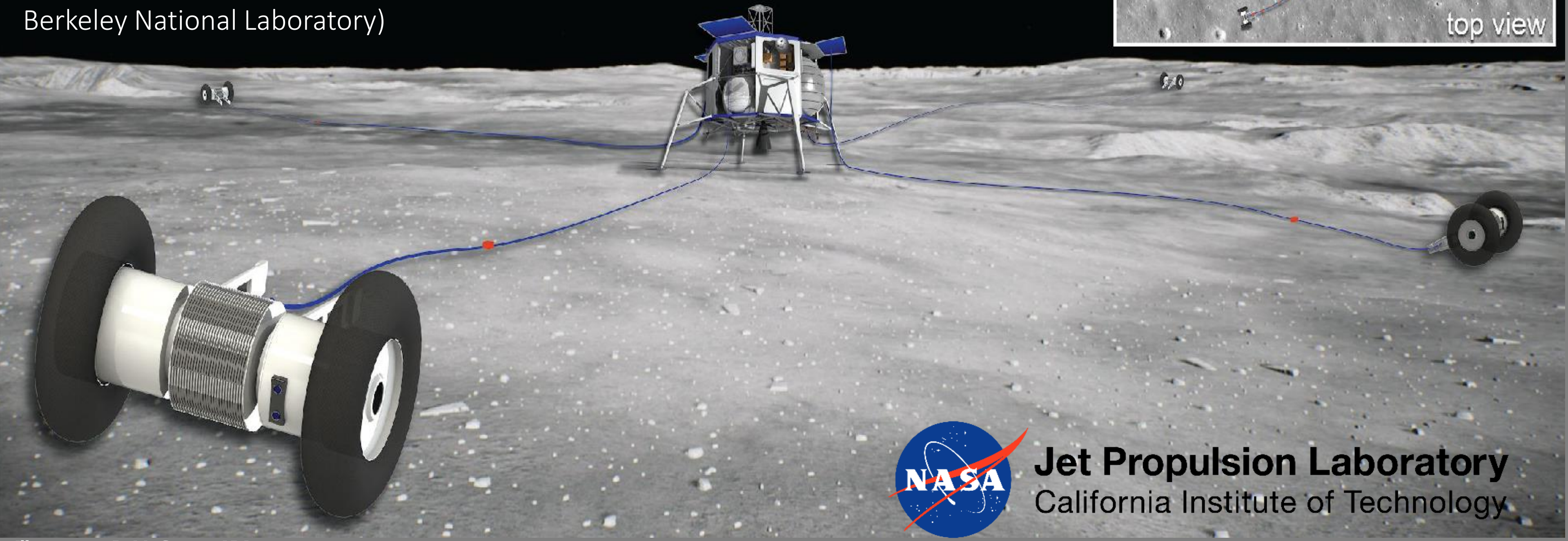
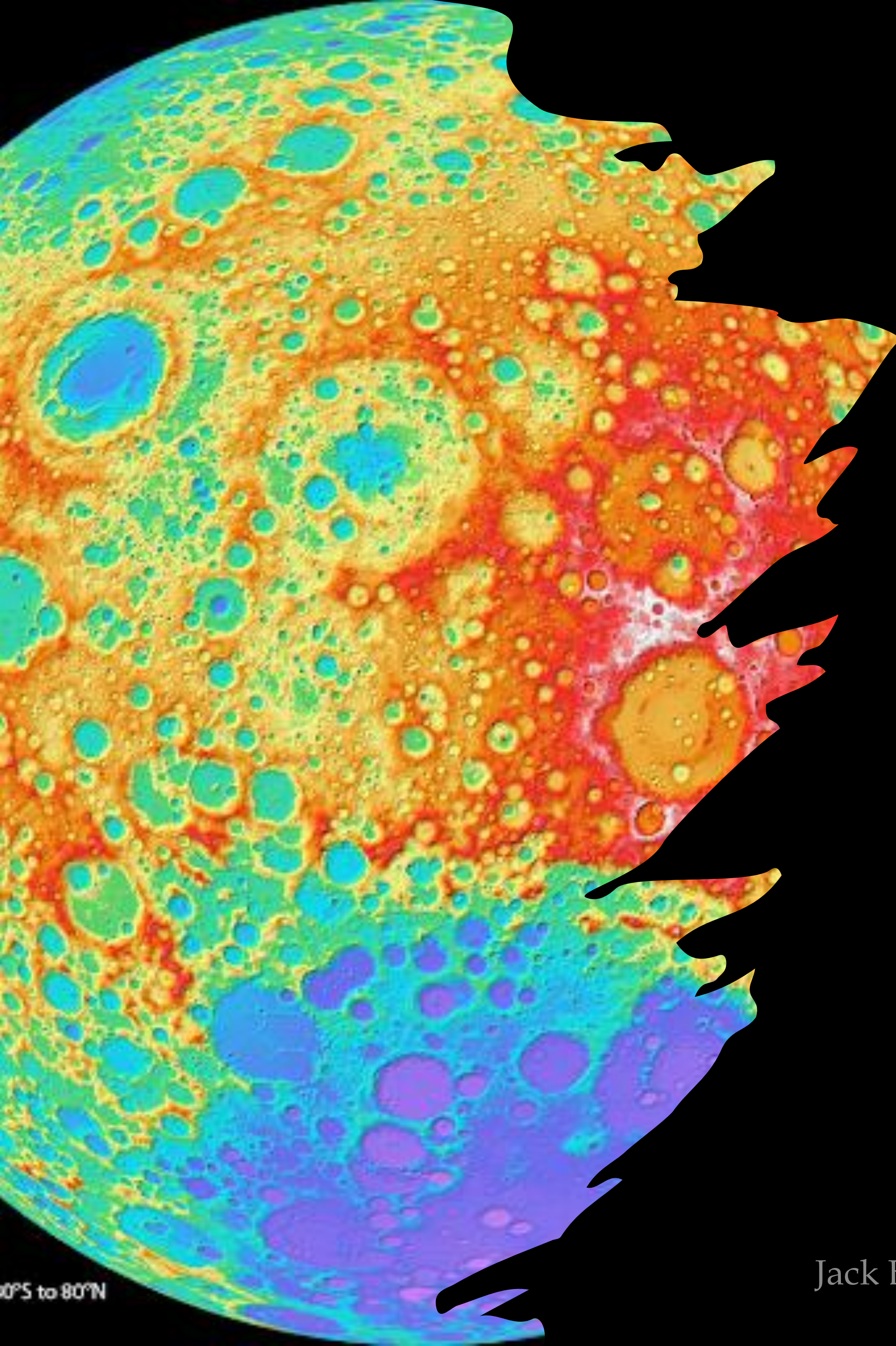


Illustration: P. McGarey, JPL

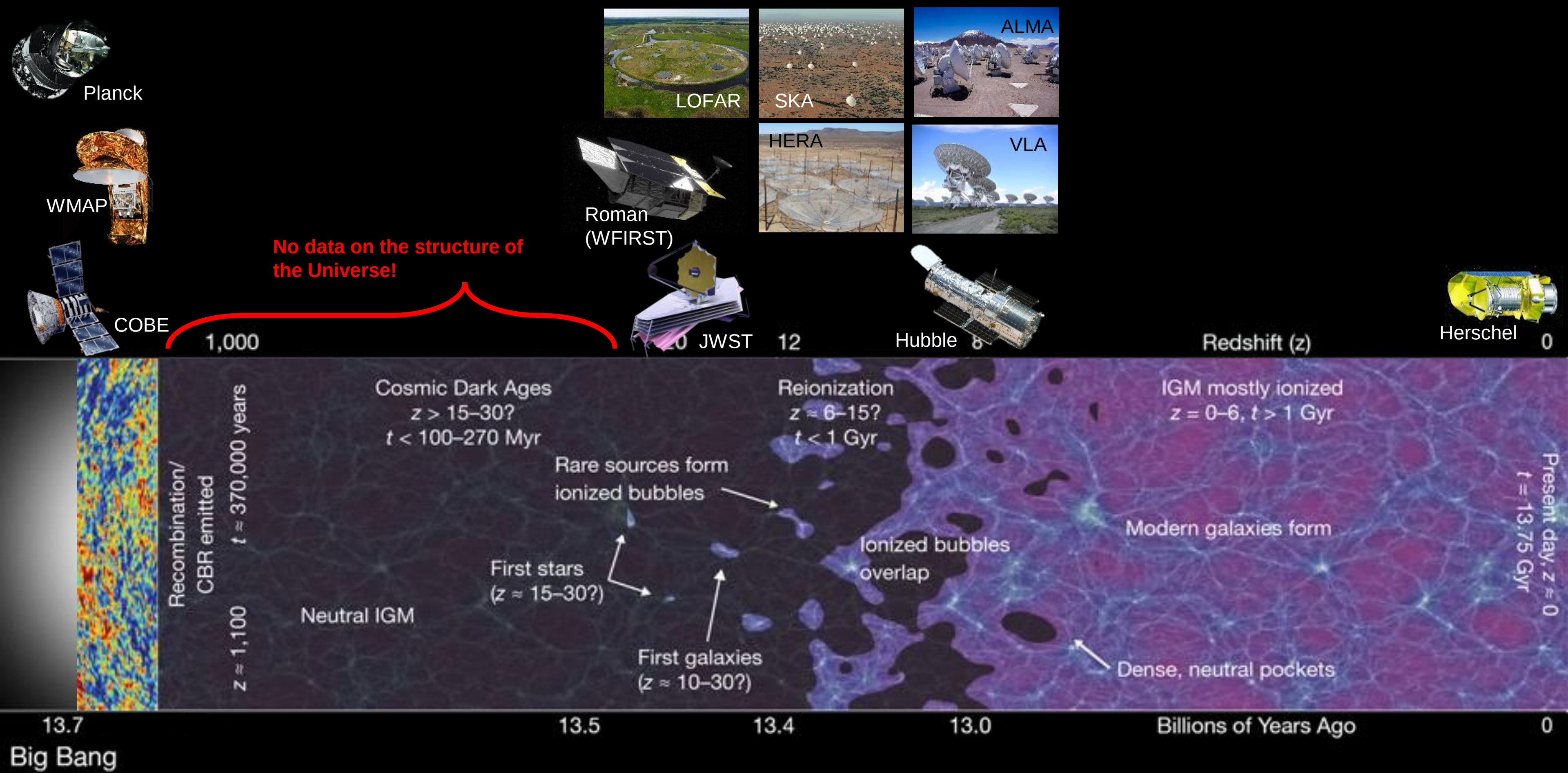
Burns, MacDowall, Bale, Hallinan, Bassett, Hegedus, 2021, *Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions,* Planetary Science Journal, 2:44, arXiv:2102.02331



Access to the lunar farside provides an unparalleled opportunity to perform low radio frequency astrophysics & cosmology due to the

- unique radio-quiet,
- lack of a significant ionosphere,
- dry, stable environment.
- mitigation of plasma noise from solar wind

Evolution of the Universe



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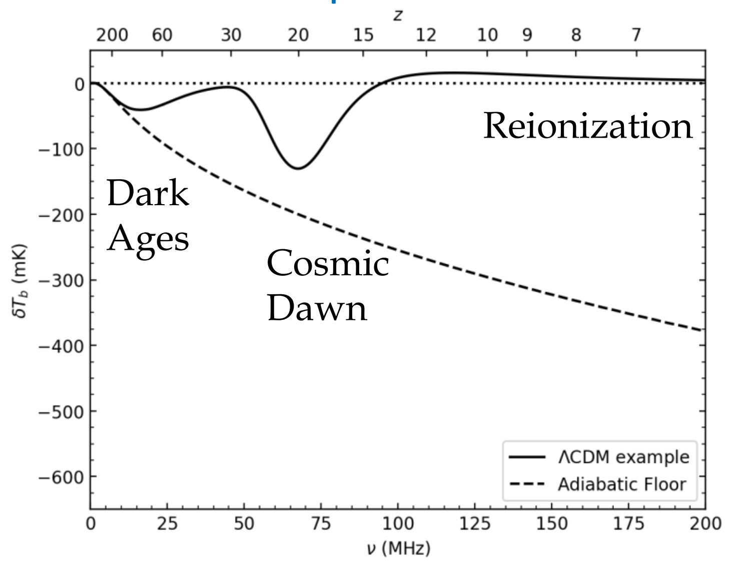
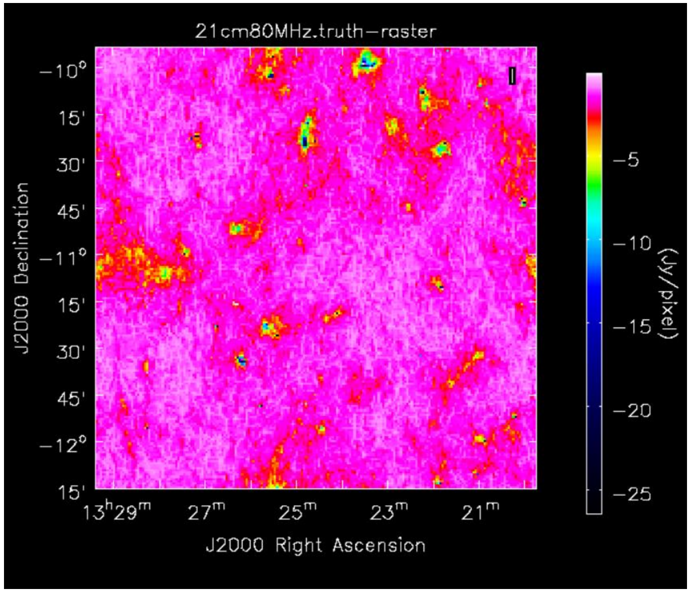
FARSIDE Array Provides Two Complementary Methods to Observe the Dark Ages

Global or Sky-averaged 21-cm Frequency Spectrum



3-D Spatial & Spectral Fluctuations in the 21-cm Signal



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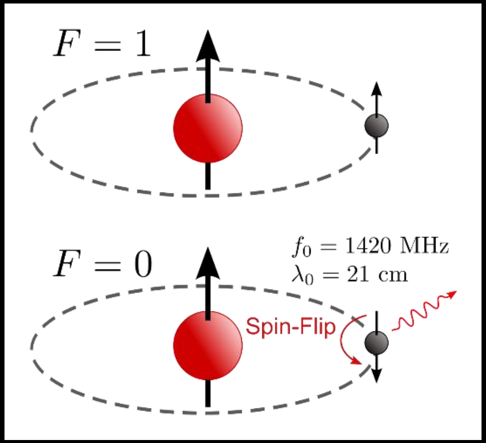
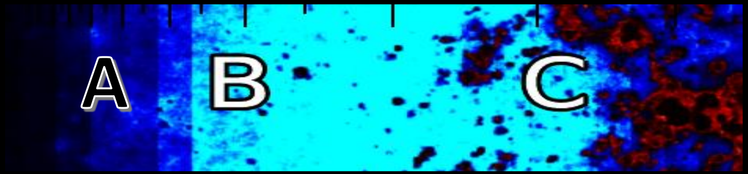
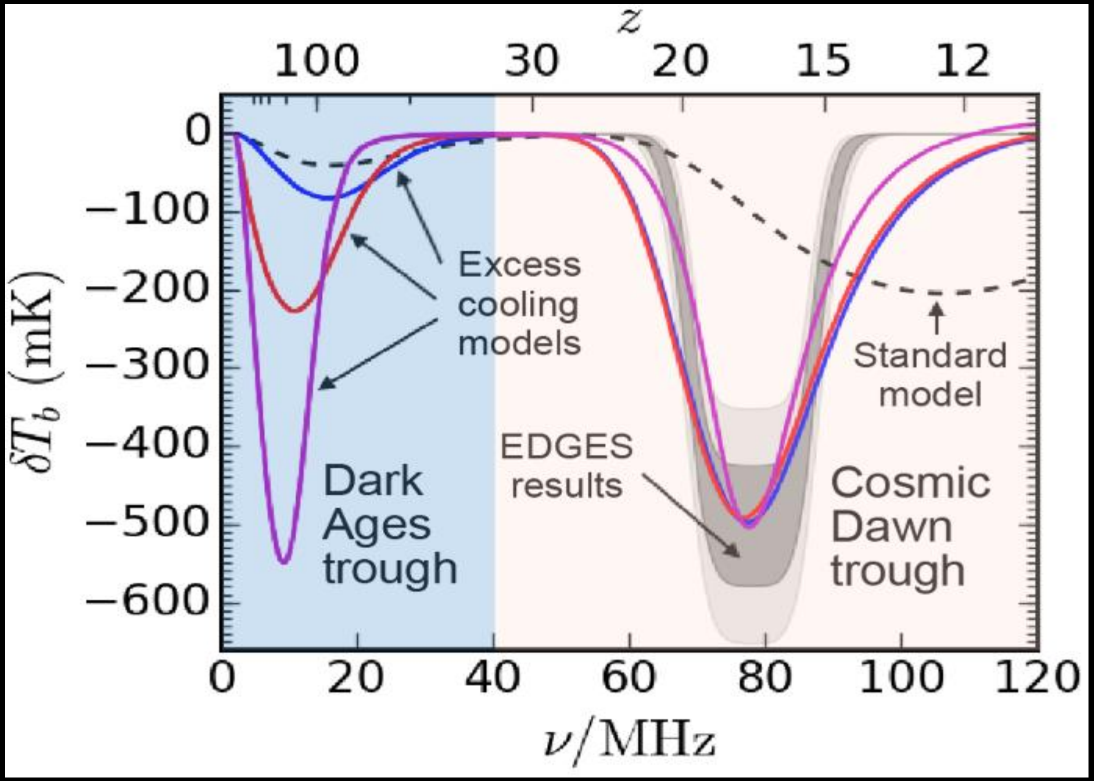
The Global 21-cm signal

Spectral Features







A: Dark Ages: test of standard cosmological model

B: Cosmic Dawn: First stars ignite

C: Black hole accretion begins

EDGES: Bowman et al. 2018, Nature, 555, 67.

How to amplify signal by a factor of 2-3 to explain EDGES results?

$$\delta T_b \simeq 27\ \overline{x}_{\mathrm{H\ I}}(1+\delta)\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_{\mathrm{R}}}{T_{\mathrm{S}}}\right)\ \mathrm{mK}$$

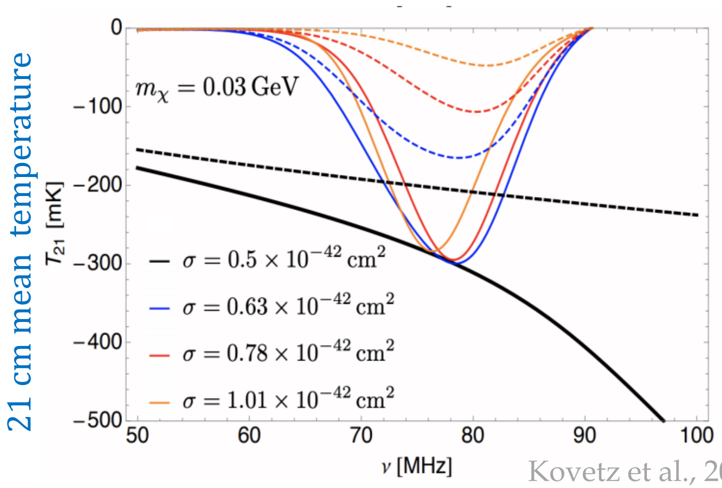
1. Increase T_R via Dark Matter decay or synchrotron radiation from black holes, galaxies.
    - Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto

2. Alter the cosmology.
    - McGaugh, Costa et al., Hill et al.

3. Decrease T_S via baryon-Dark Matter interactions which cools the hydrogen.
    - Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slatyer & Wu

Probing Exotic Physics in an Unexplored Regime

Dark Matter - Baryon Interaction Beyond Gravity



Kovetz et al., 2019

Solid line:
Models with baryon dark matter interaction

Dashed line:
Models without baryon dark matter interaction

- Measuring the 21-cm signal will enable new powerful probe of dark matter physics (Slayer 2016) enabling tests different particle physics models of dark matter in unconstrained regime:
  - Dark matter annihilation (or decay) rate is higher in the denser, high-redshift Universe (Crelli et al. 2019). By-products of decay (or annihilation) will heat and ionize the gas, imprinting characteristics signature in the 21 cm signal.
  - Non-minimal interaction between dark matter and baryon also leads to a modified 21 cm signal (Tashiro et al. 2014).
  - If dark matter is warm and has a larger coherence scale (ultra-light axions, sterile neutrinos), then star formation is delayed which leads to an extended Dark Ages.

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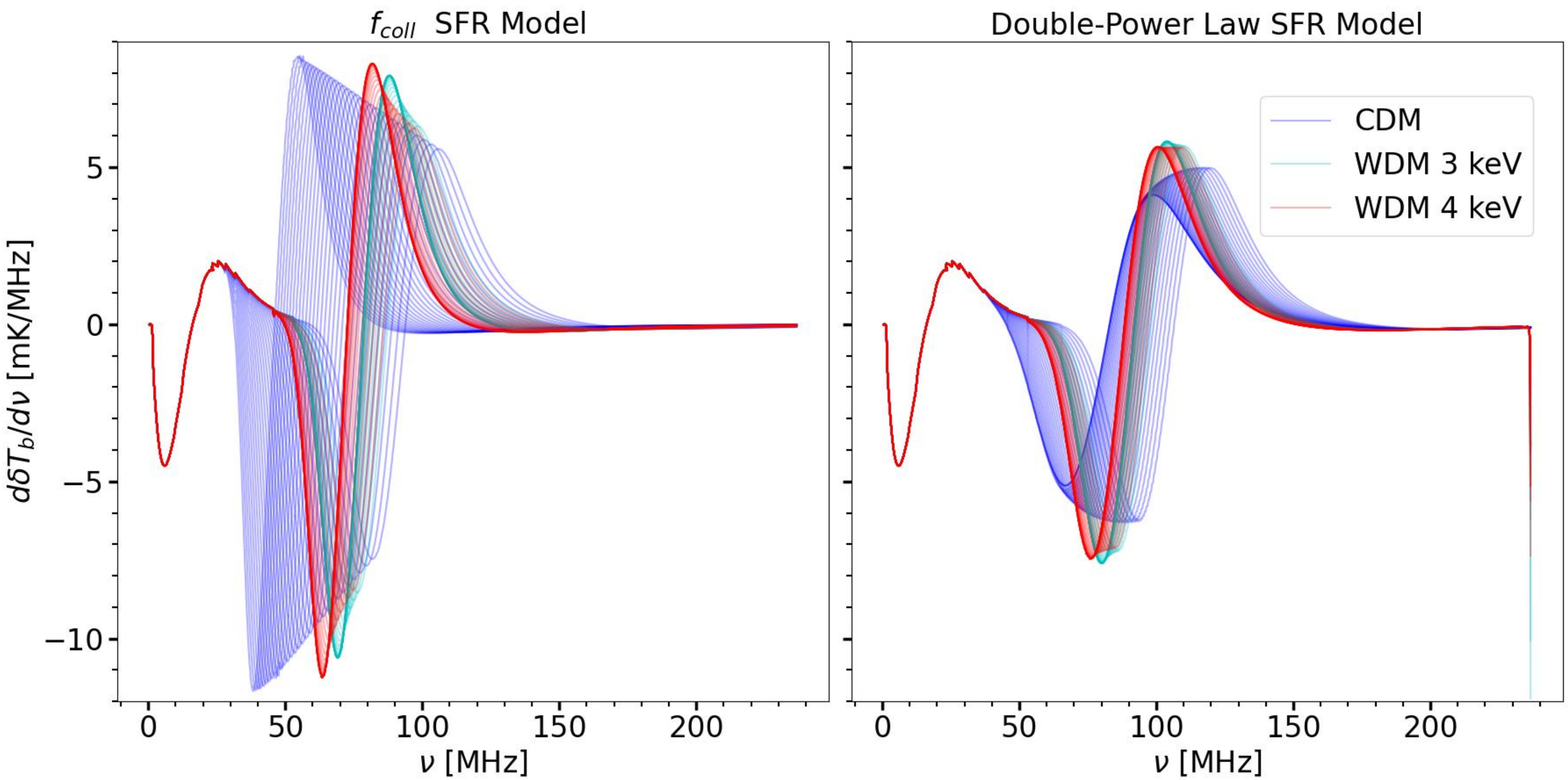
Separating Effects of CDM, WDM, & Star Formation



Models from Hibbard, Mirocha, Rapetti, Tauscher, Burns

Spatial Evolution of Hydrogen in the Early Universe

Credit: Marcelo Alvarez

Probing Fundamental Physics with 21 cm Signal in the Dark Ages

- After the *Planck* mission final results, the standard Cold Dark Matter cosmology is very well constrained.

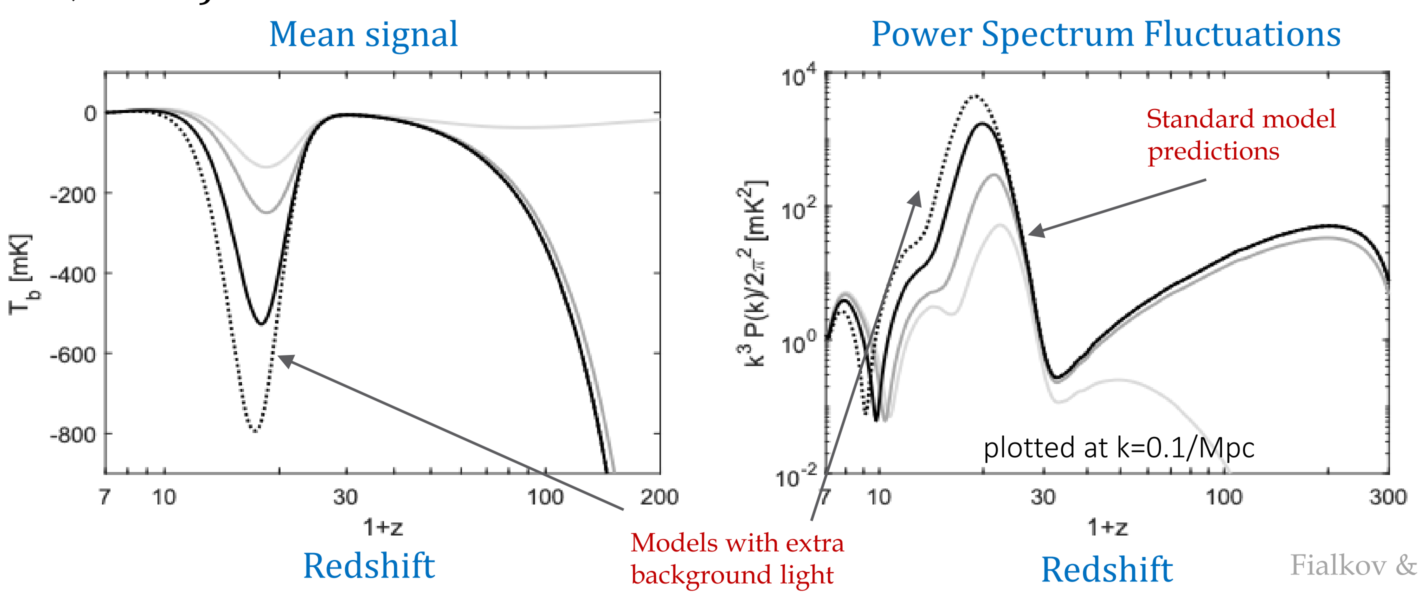
- It enables precise calculation of the shape of the 21 cm signal as a function of frequency (or equivalently redshift) and scales during the Dark Ages.

- 21 cm signals in the dark ages accesses a very large cosmological volume and samples many linear modes of the density perturbations. It will potentially enable detailed measurements of the scale dependence of primordial fluctuations and their possible deviations from Gaussian statistics (Meerburg et al., 2016, 2017), and signatures of primordial gravitational waves (Schmidt et al. 2014, Hirata et al., 2018).

- This promises novel insights into the inflationary phase and unknown physics of the early Universe.

Testing the Standard Cosmological Model in an Unexplored Regime

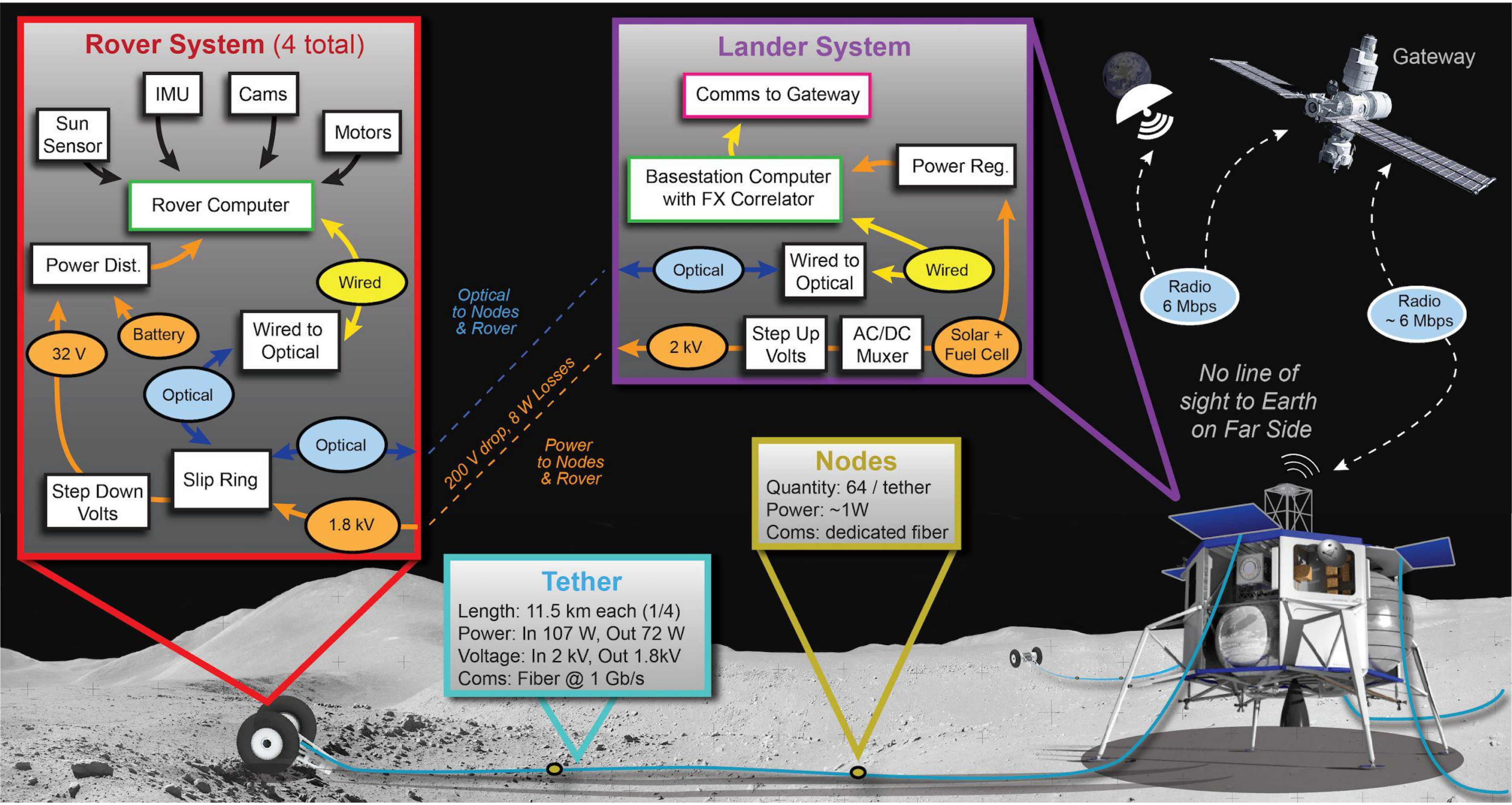
- Extra radio background radiation could be contributed by neutrinos radiative decay into sterile neutrinos (Chianese et al. 2019), dark matter decay (Fraser et al. 2018), primordial topological defects (Brandenberger et al., 2019).



Fialkov & Barkana, 2019

FARSIDE Mission Architecture

Frequencies: 100 kHz to 40 MHz



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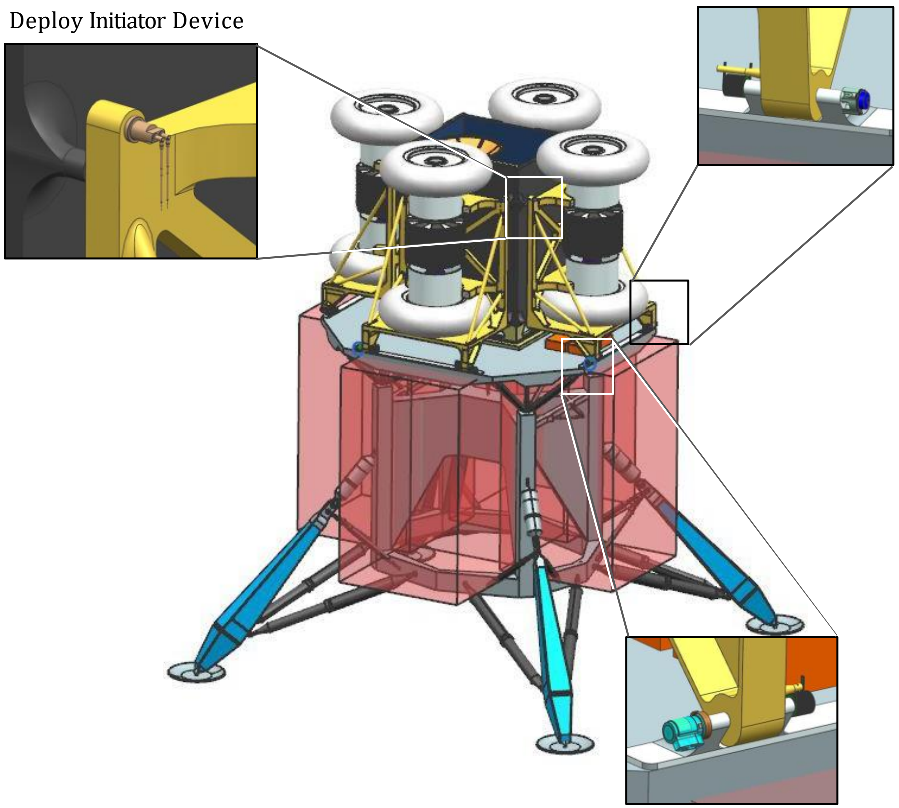
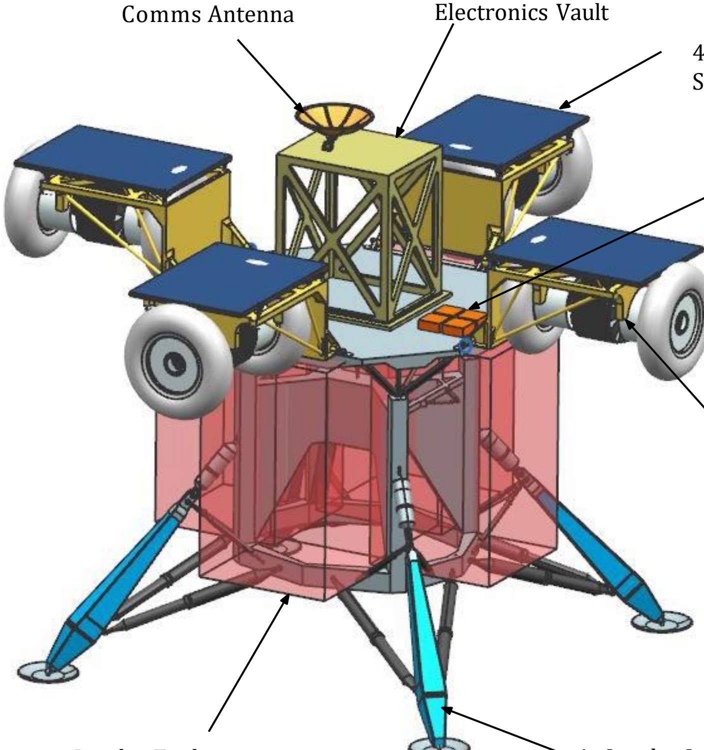
Lander/Rover Configuration Overview

Stowed/Landing Configuration

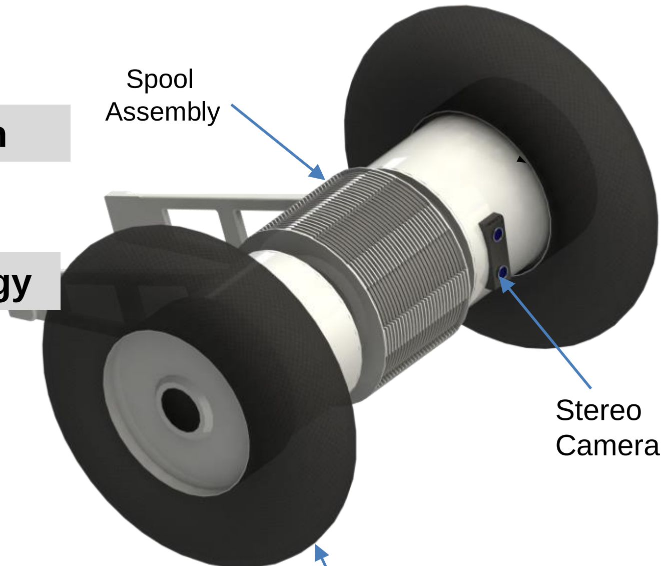


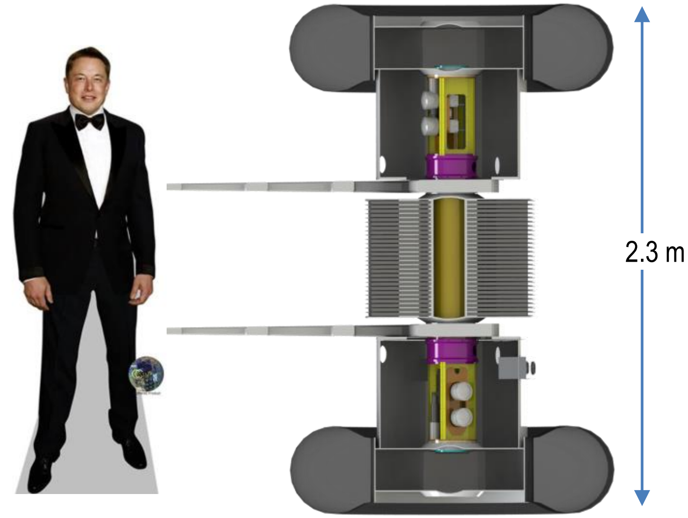
Mid-Deploy Configuration

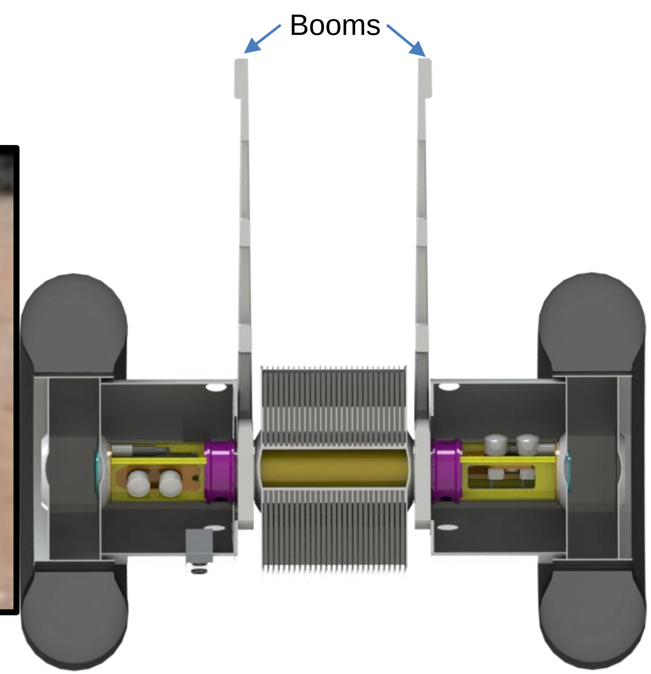


Design Strategy

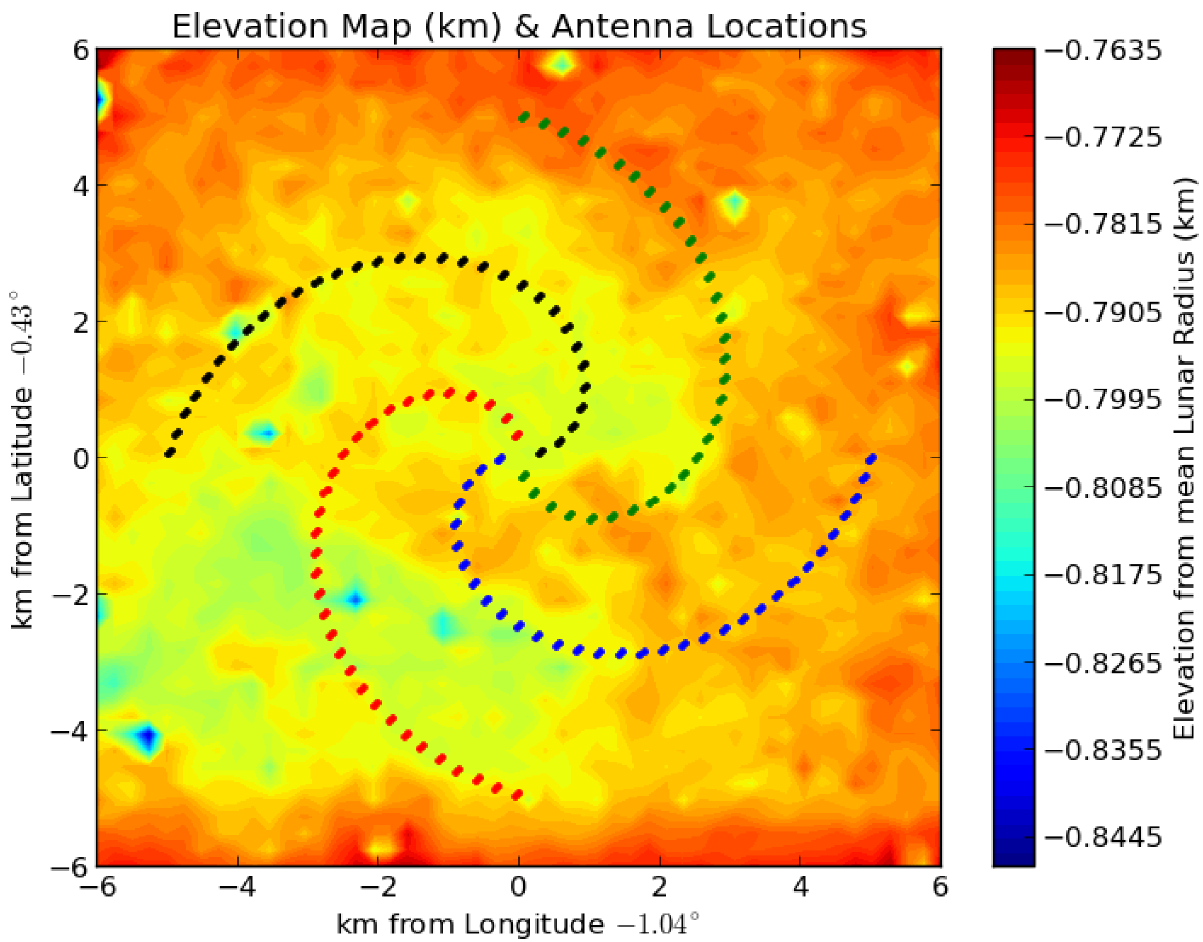
Node Sizing
↓
Node / Tether Integration
↓
Spool Deployment Strategy
↓
Spool Sizing
↓
Rover Design
↓
Egress Strategy
↓
Lander Accommodations
↓
Lander Configuration



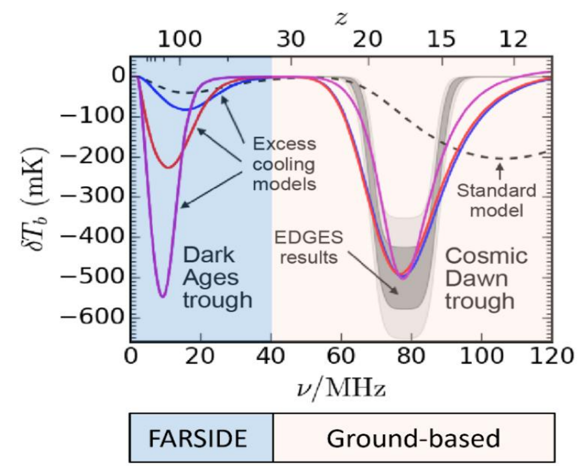




FARSIDE Simulations



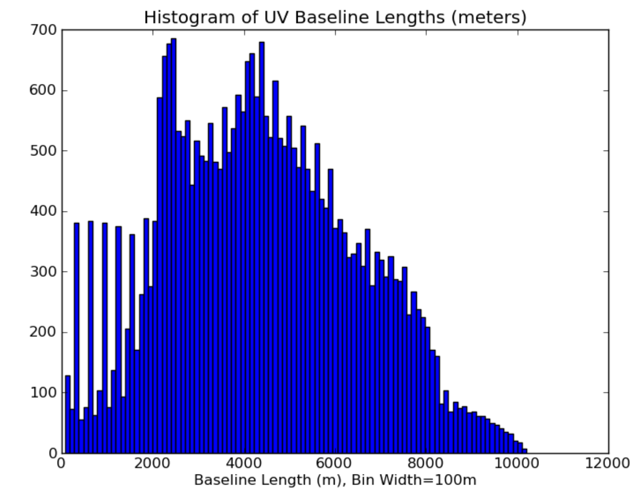
$$\sigma = \frac{2\, k_B\, T_{sys}}{\eta_s\, A_{eff}\, \sqrt{N(N-1)(N_{IF}\, \Delta T\, \Delta\nu)}}$$

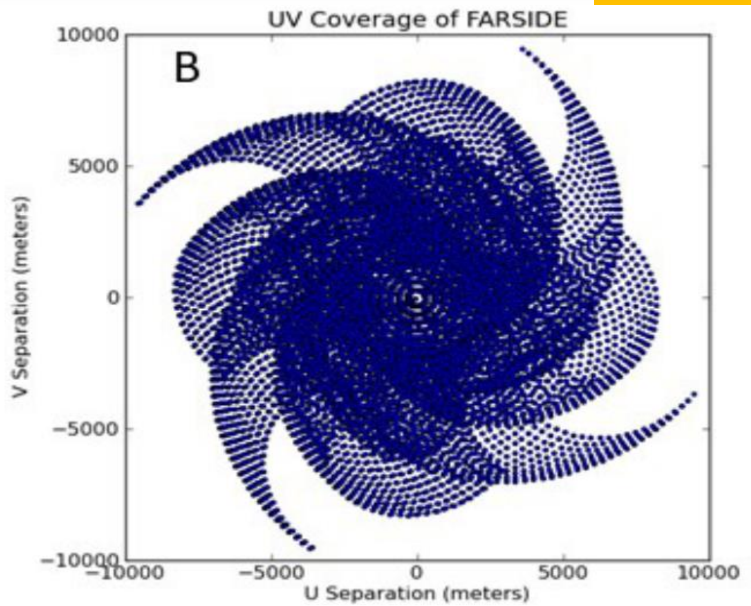


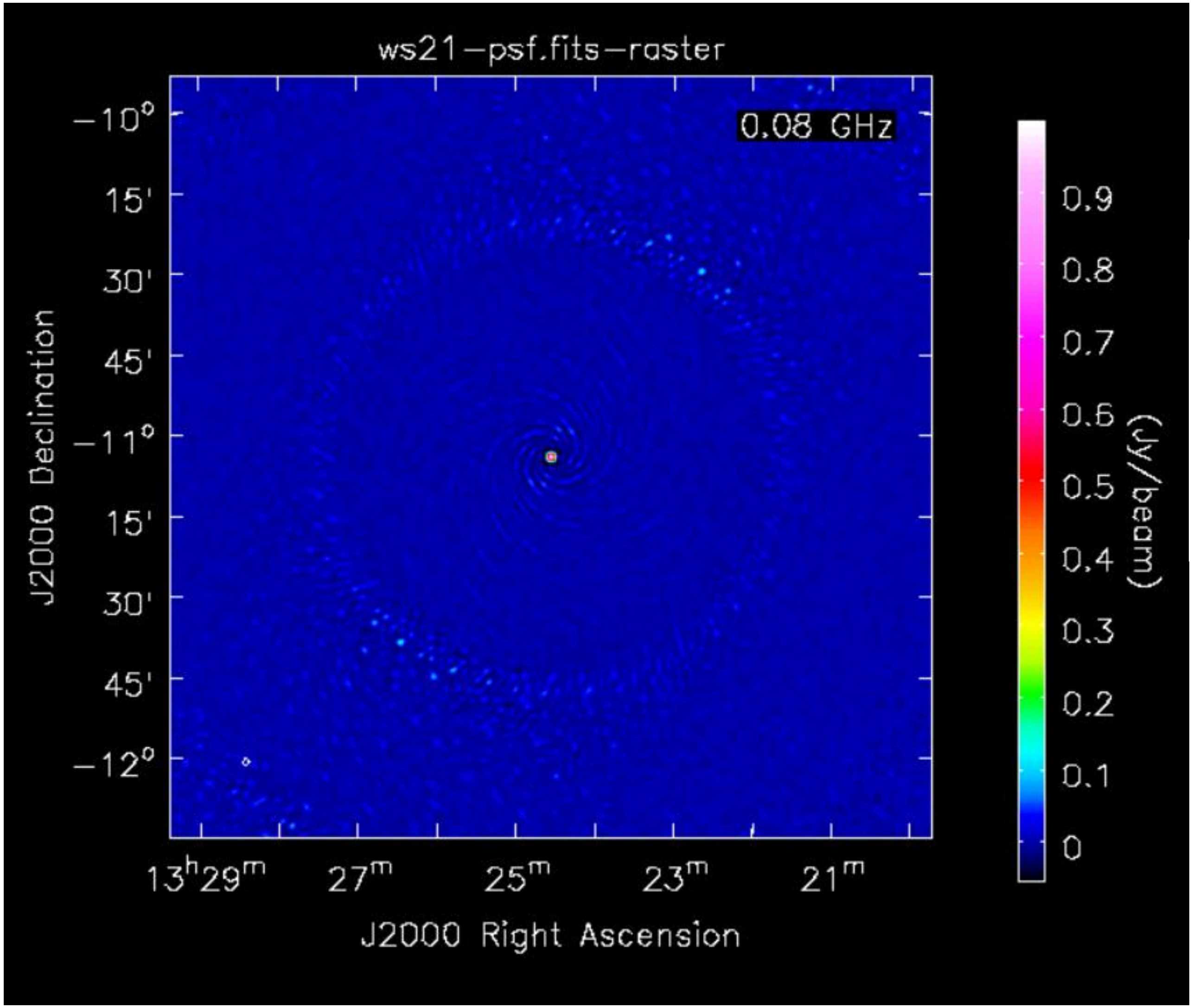
Simulations by Hegedus, Chang, Burns, Hallinan

UV Coverage

- Generally, logarithmic & more short baselines improve SNR
- Can use calibration routines to fit for antenna after the fact, low precision possible
- Lines of dipoles, all same length fine
- Image is instantaneous u-v coverage.





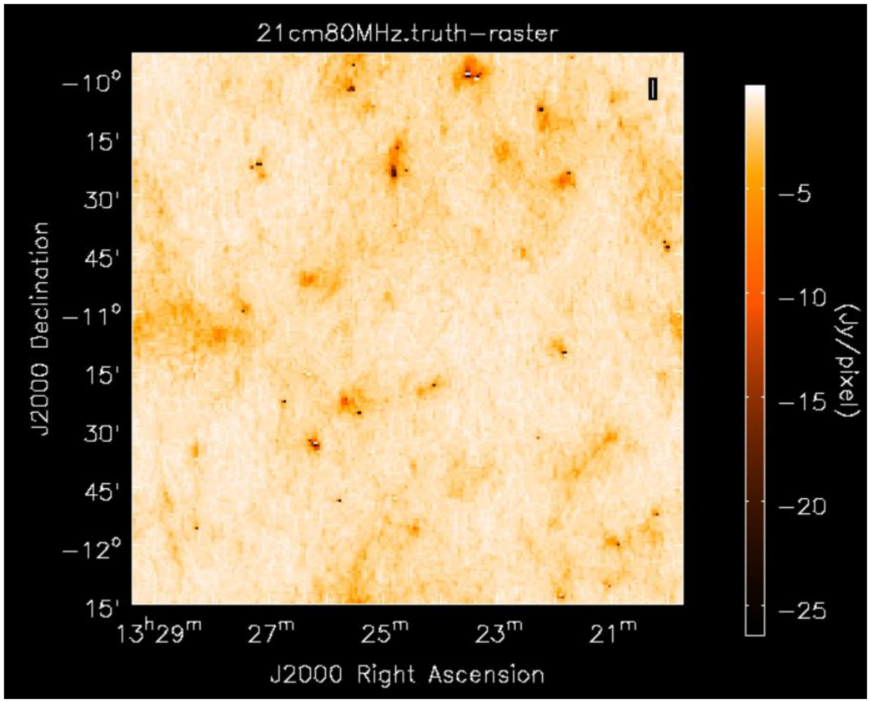


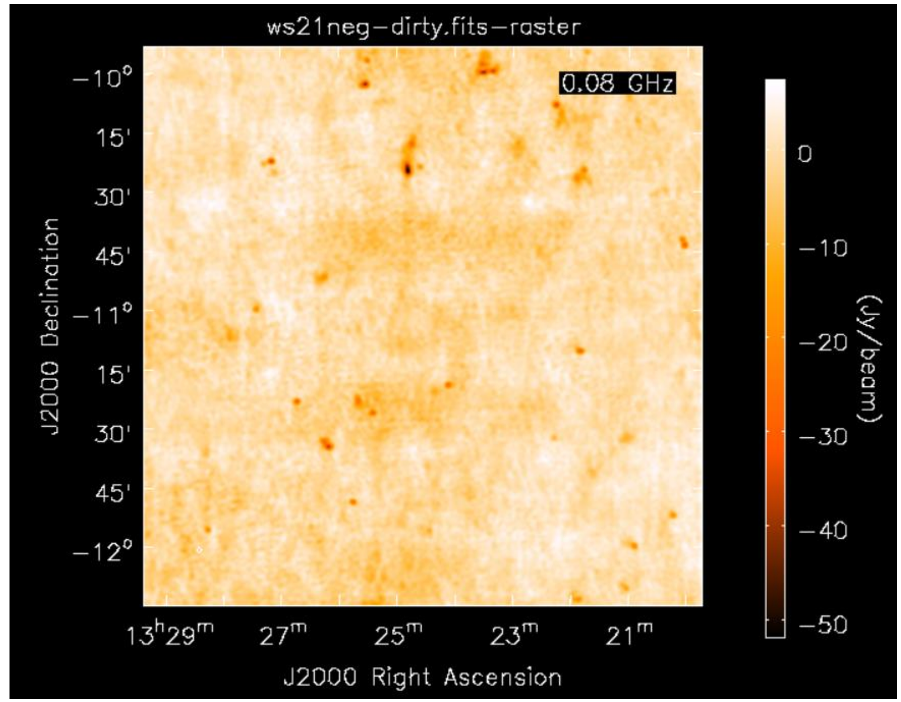
Frequency	Beam Width, arcsec
100 kHz	55,255.2
10 MHz	552.552
40 MHz	138.138
80 MHz	69.069

FARSIDE Sensitivity at 15 MHz

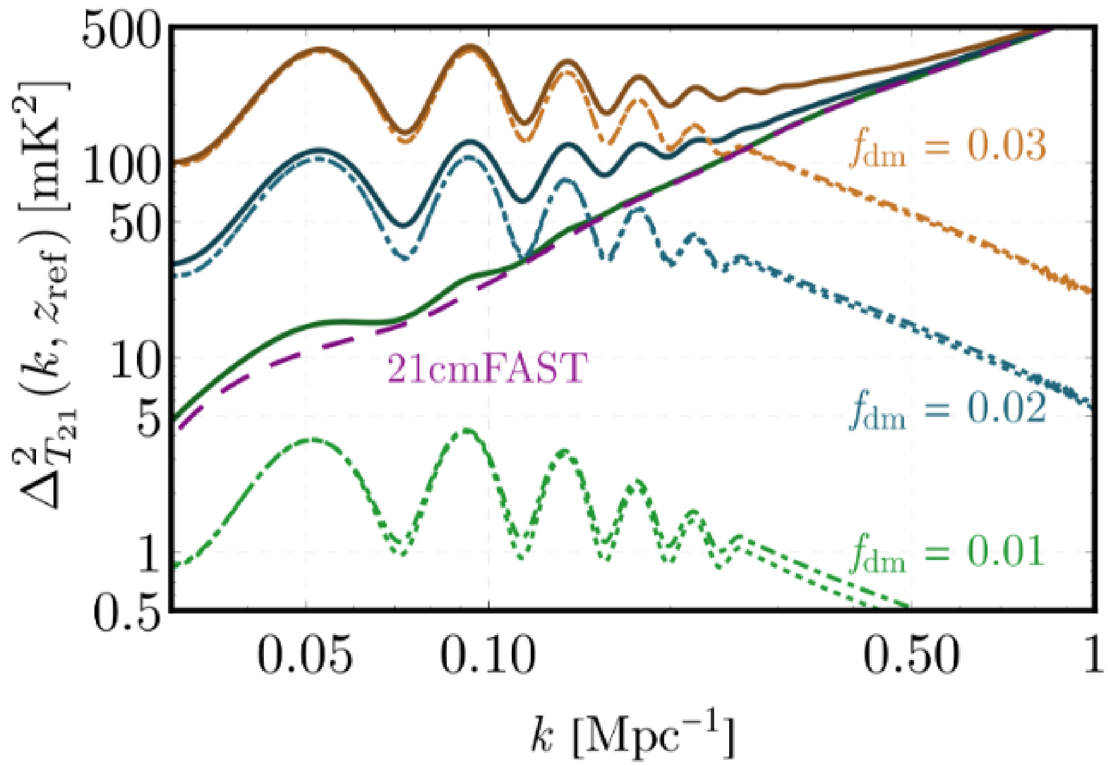
Quantity	Value
Frequency Coverage	0.1 – 40 MHz (1400 × 28.5 kHz channels)
System Temperature (T_{sys})	2.7×10^4 K
Effective Collecting Area (A_{eff})	2240 m^2
System Equivalent Flux Density ($2k_BT_{sys}/A_{eff}$)	2.8×10^4 Jy
1σ Sensitivity for 1 hour, Δν=ν/2	120 mJy

Truth to Noiseless Dirty Image, 80 MHz



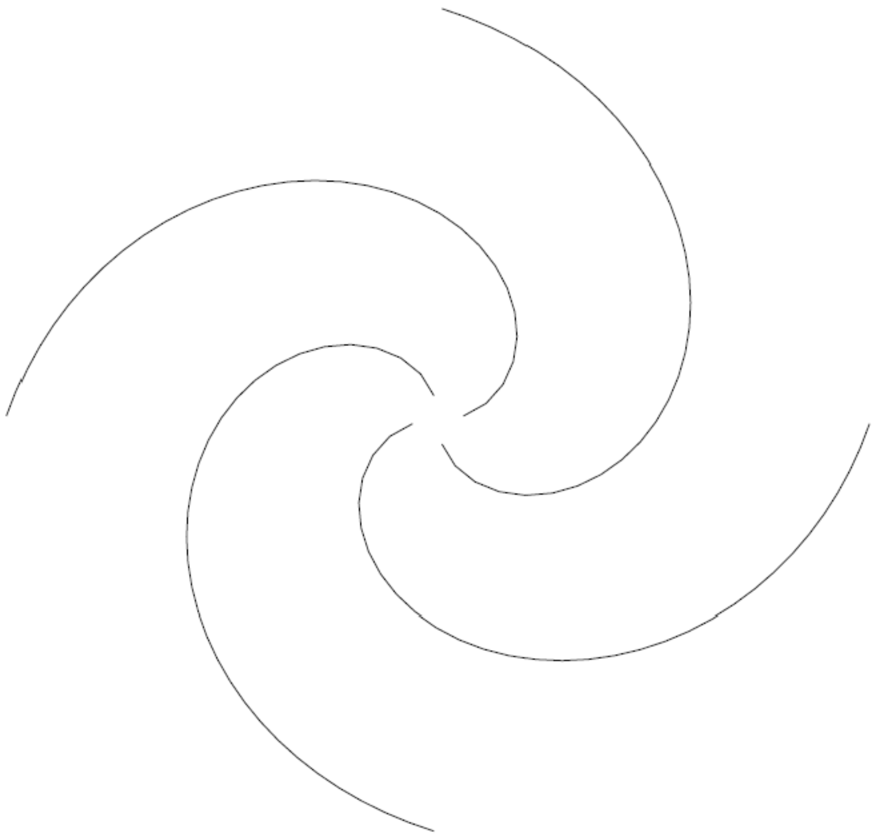


Models of the Fluctuation Power Spectrum

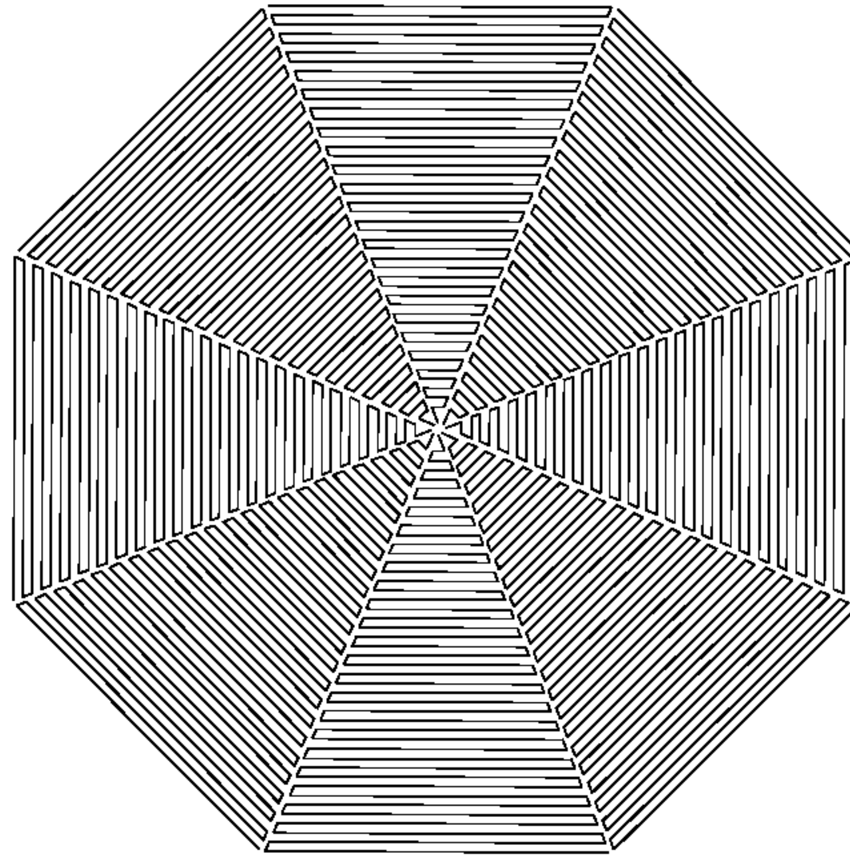


The 21-cm power spectrum can distinguish between different exotic physics scenarios during the Dark Ages. Fraction f_{dm} of the dark matter is assumed to have a small charge; the oscillations in the power spectrum arise from the large-scale streaming of baryons relative to dark matter. The solid curves are the total power for each value of f_{dm}, after linearly adding the dash-dotted lines, showing the contributions from dark matter-baryon scattering, to the standard cosmological model (labeled "21cmFAST"). Figure from Muñoz et al. (2018). Reference z=17.

FarView: A Radio Array of 100,000 dipoles



FARSIDE
128 dual polarized antennas - 100m per polarization
4 rovers - 8.9 km per rover

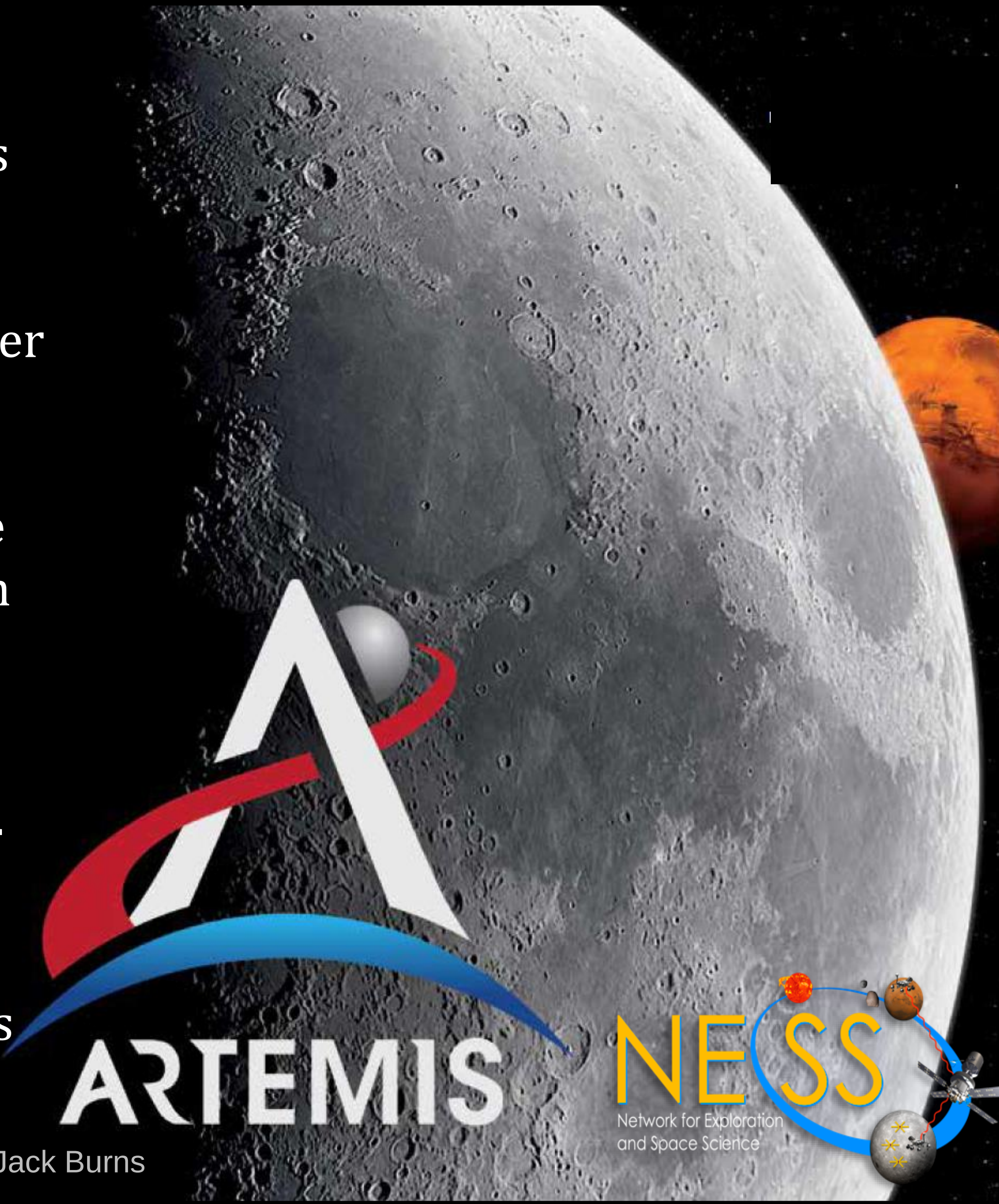


Farview
100,000 dual polarized antennas - 5m per polarization
8 rovers - 125 km per rover

NIAC P.I. **Ron Polidan**, Lunar Resources
Co-Is: **J. Burns, E. Carol, A. Ignatiev**

Summary & Conclusions

- NASA, ESA, & other space agencies are committed to new explorations of the Moon in this decade.
- NASA Commercial Lunar Payload Services (CLPS) program will deliver science payloads to the surface of the Moon beginning in Q4 2021.
- FARSIDE will take advantage of the transportation and communication infrastructure associated with NASA's Artemis.
- FARSIDE & FarView will measure the 21-cm spectrum in total power mode; and will measure 3-D Fluctuations spatial/spectral fluctuations to explore new physics including multiple flavors of dark matter, neutrinos, & inflation.



FARSIDE Science Cases

Imaging Type II/III Solar Radio Bursts

Auroral Radio Emissions from Saturn, Uranus, & Neptune; lightning; Planet 9?

Magnetospheres & Space Weather Environments of Habitable Exoplanets

Sounding of the Lunar Subsurface

Measuring farside lunar quakes with Distributed Acoustic Sensing.

Tomography of the ISM

Dark Ages Hydrogen Cosmology