Lunar Array for Radio Cosmology

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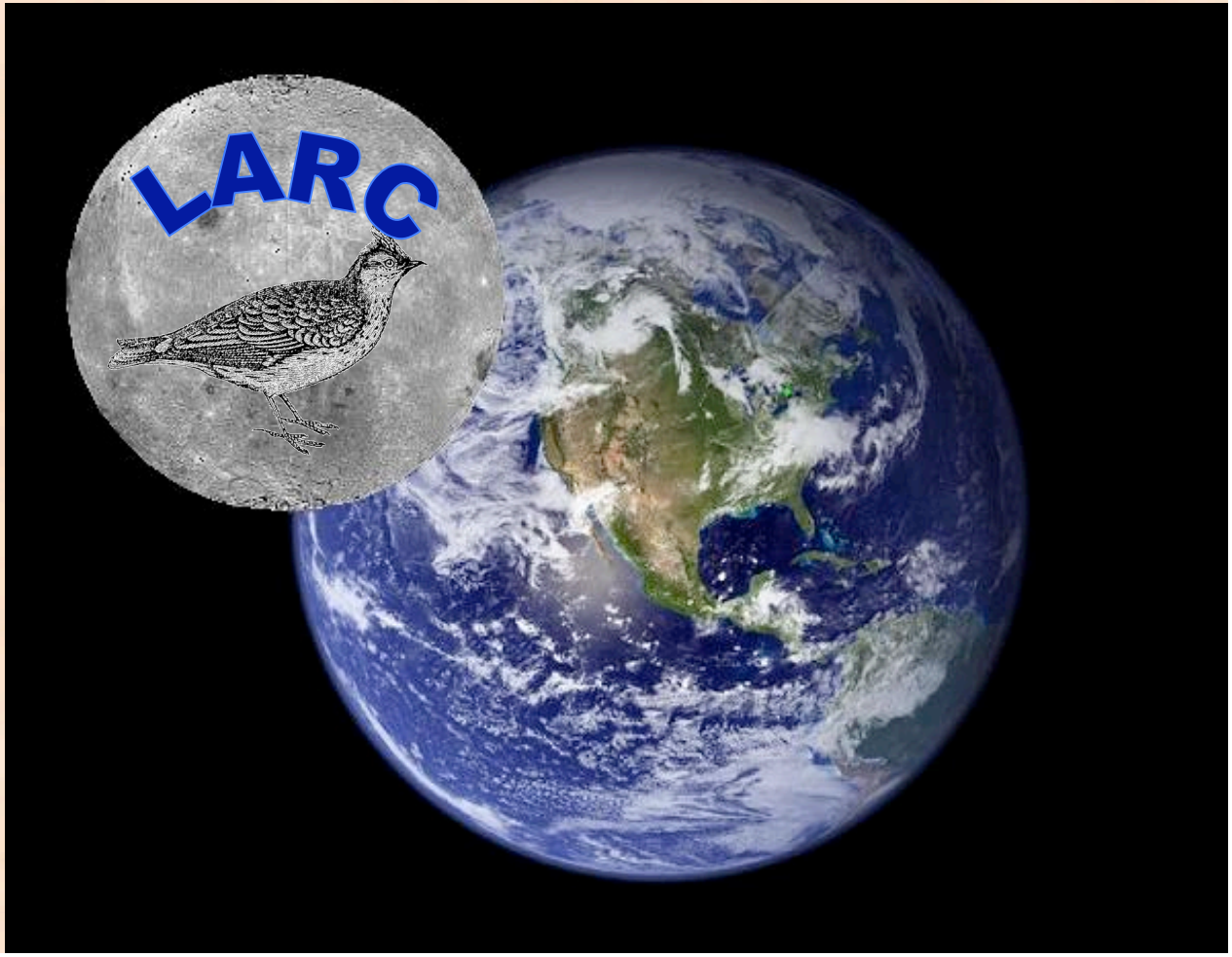
for the LARC Collaboration



One of two Lunar Radio Array concepts studied as part of NASA's program for Astrophysics Strategic Mission Concepts Studies

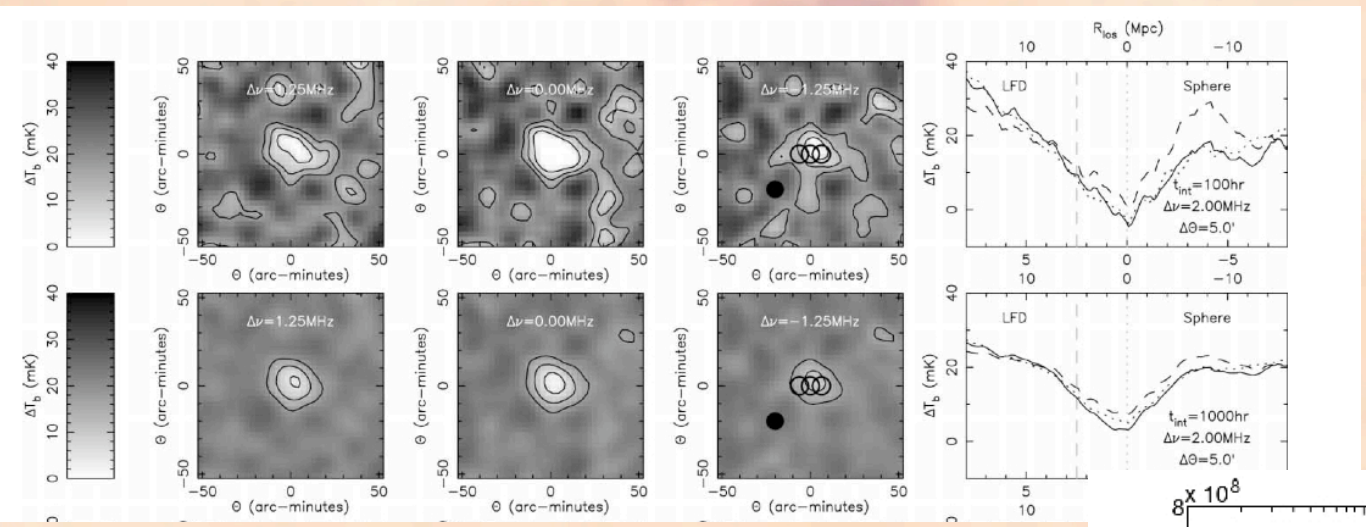
LARC Group

Don Backer
Jeff Booth
Rich Bradley
Chris Carilli
Angelic de Oliveira Costa
Olivier de Weck
Peter Ford
Rick Foster
Bob Goeke
Jackie Hewitt
Jeff Hoffman
Charles Lawrence
Gene Lee
Avi Loeb
David Miller
Miguel Morales
Max Tegmark
Joel Villasenor
Matias Zaldarriaga
Maria Zuber

See Dark Ages Lunar Interferometer (DALI) poster by Lazio et al.

Fundamental Motivation is to do Cosmology

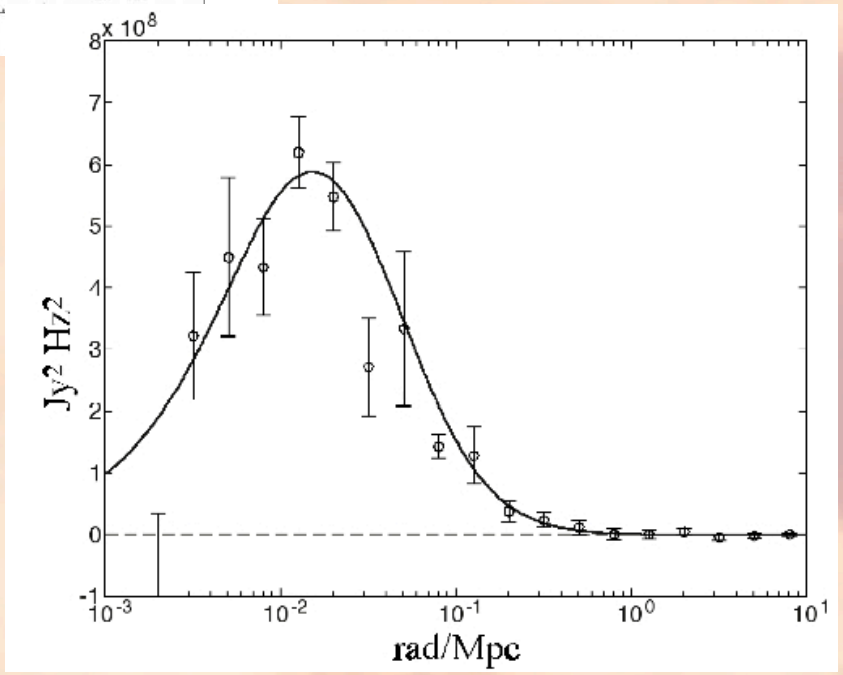
(but lots of other science, too)



Wyithe, Loeb, and Barnes (2006)

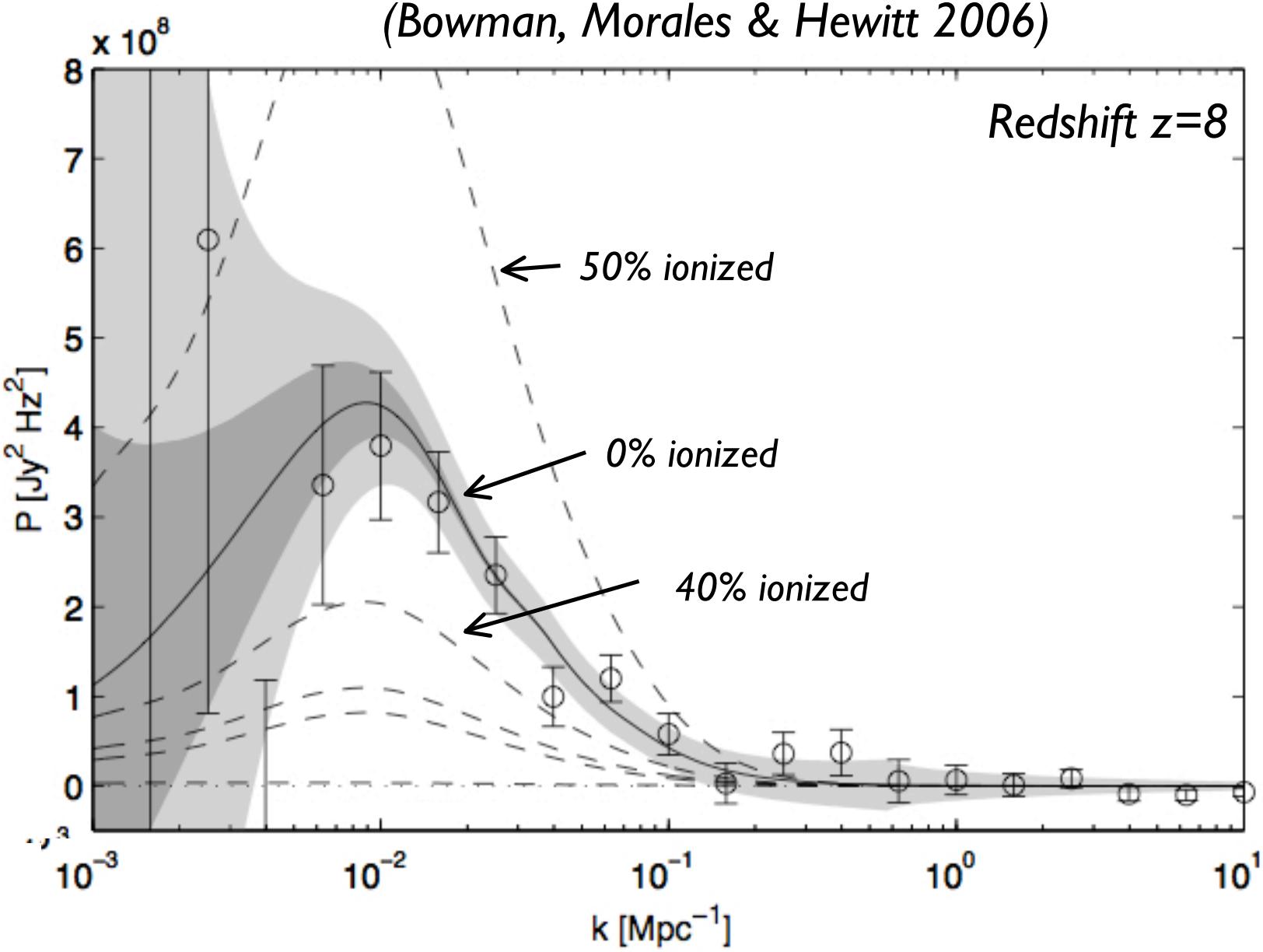
Detection of individual features

Statistical detection of structures



MWA NSF proposal (2004)

Murchison Widefield Array Sensitivity
(Bowman, Morales & Hewitt 2006)



Power

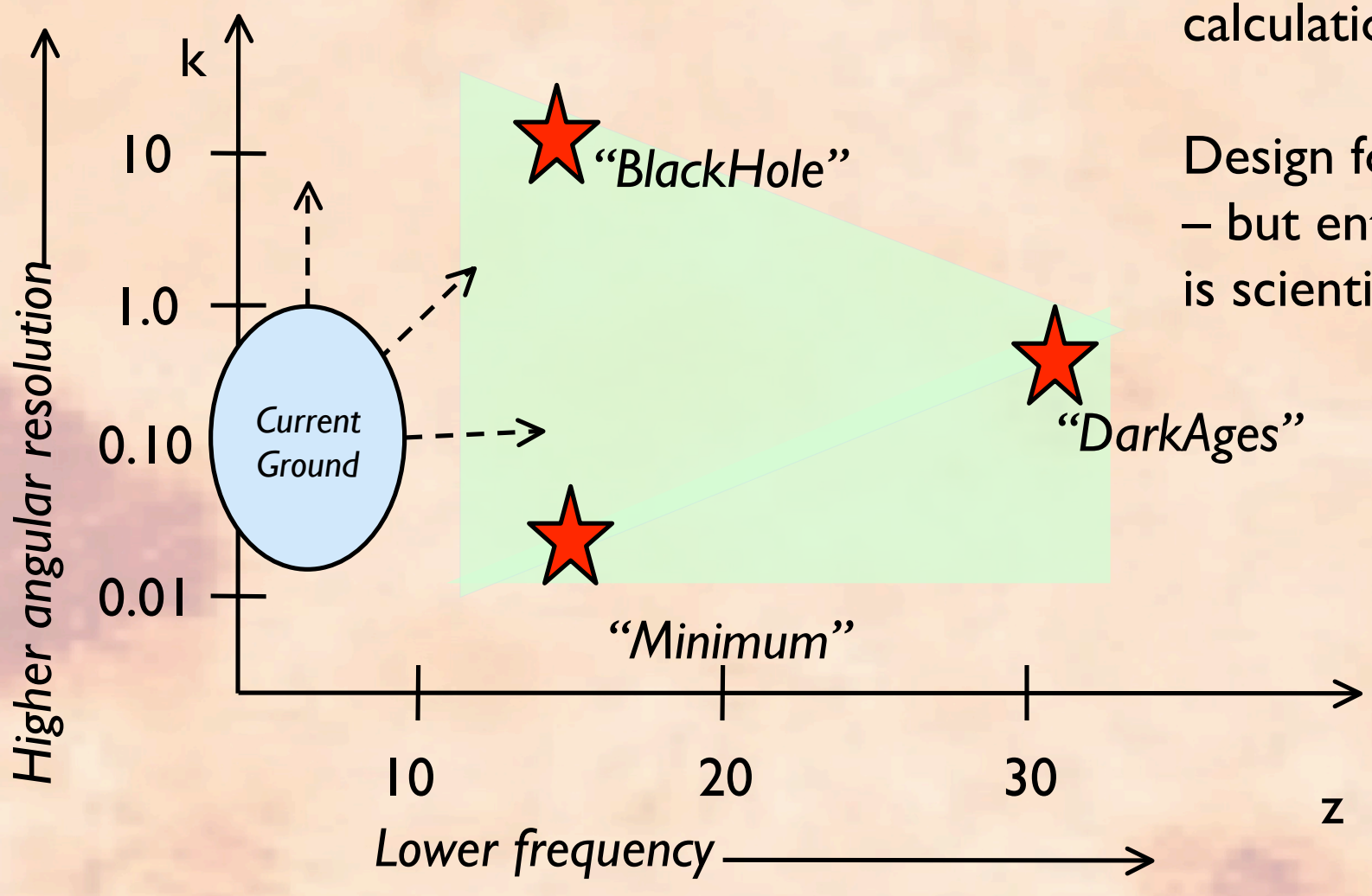
Inverse spatial wavelength (proportional to angular scale on sky of fluctuation)

Fiducial Lunar Arrays

Minimum interesting array depends on limits of ground-based arrays – unknown – so guess

k-z space of experiment and J. Bowman's power spectrum sensitivity calculations

Design for fiducial point – but entire shaded area is scientifically interesti



LARC Concept:
Boundaries set by three fiducial arrays

	z	f (MHz)	N	dA (m^2)	NdA (m^2)	FOV (deg)	B_{max} (km)	Tun. Band (MHz)	Inst. BW (MHz)	τ (hrs)	Ant Dist
Minimum Design	15	88.8	410	44.3	18,200	31	2.67	88.8-129	8	12,000	$1/r^3$
BlackHole Design	15	88.8	20,000	44.3	886,000	31	2.67	45.8-129	16	12,000	$1/r^3$
DarkAges Design	30	45.8	17,000	167	2,839,000	31	5.18	45.8-129	16	12,000	$1/r^3$

LARC designs emphasize survey speed, retaining 30-degree field of view
Large number of elements is then the major challenge

LARC Concept

- Push for the best capability for cosmology
- ~ 10,000 antenna elements – make them autonomous
- Direct digital conversion at each antenna element
- Optical communication to transmit data to correlator – *see poster by J. Villasenor*
- Very large correlator – power consumption not an issue, but complexity may be (new algorithms area a development area)
- Transmission of data to Earth
- Robotic deployment using ATHLETEs
- Operate during lunar night, storing data for correlation during day

Technology development is part of LUNAR program
Plan submitted to astrophysics decadal survey

Tall Pole: Antenna Technology/Design

LARC design drivers:

- **MINIMIZE MASS AND VOLUME**
- Autonomy – low maintenance, robustness to failure of one element
- Ease of deployment
- Use vertical dimension for gain to reduce footprint

LARC Choice: small arrays of self-deploying helices

See poster by J. Lazio for DALI's printed dipole concept

Self-Tending Array Node and Communications Element (STANCE)

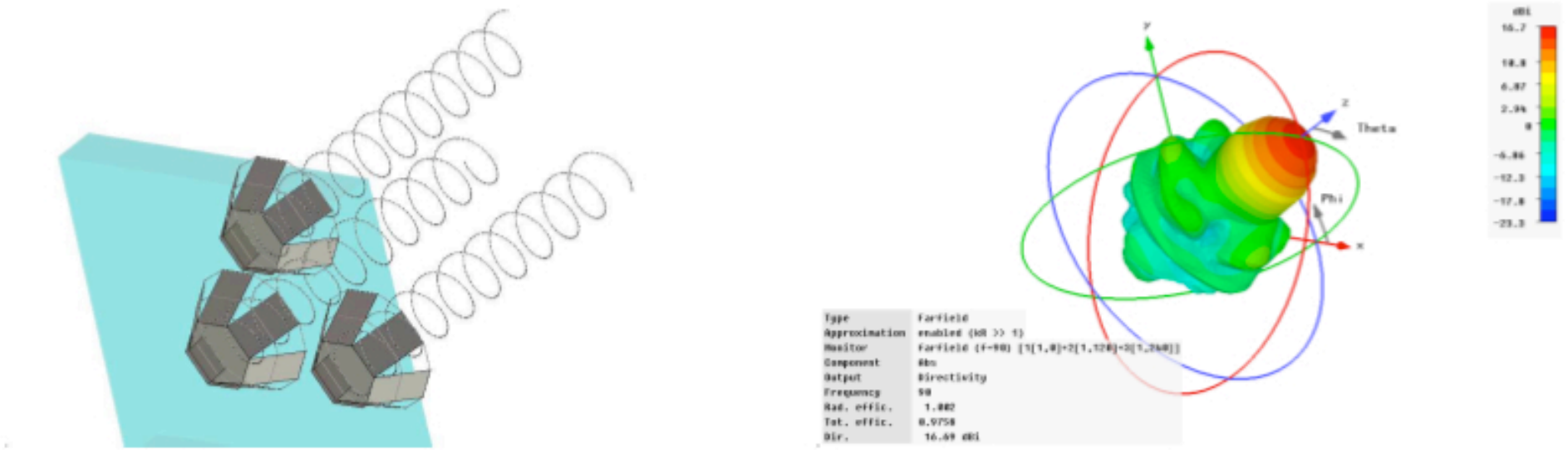
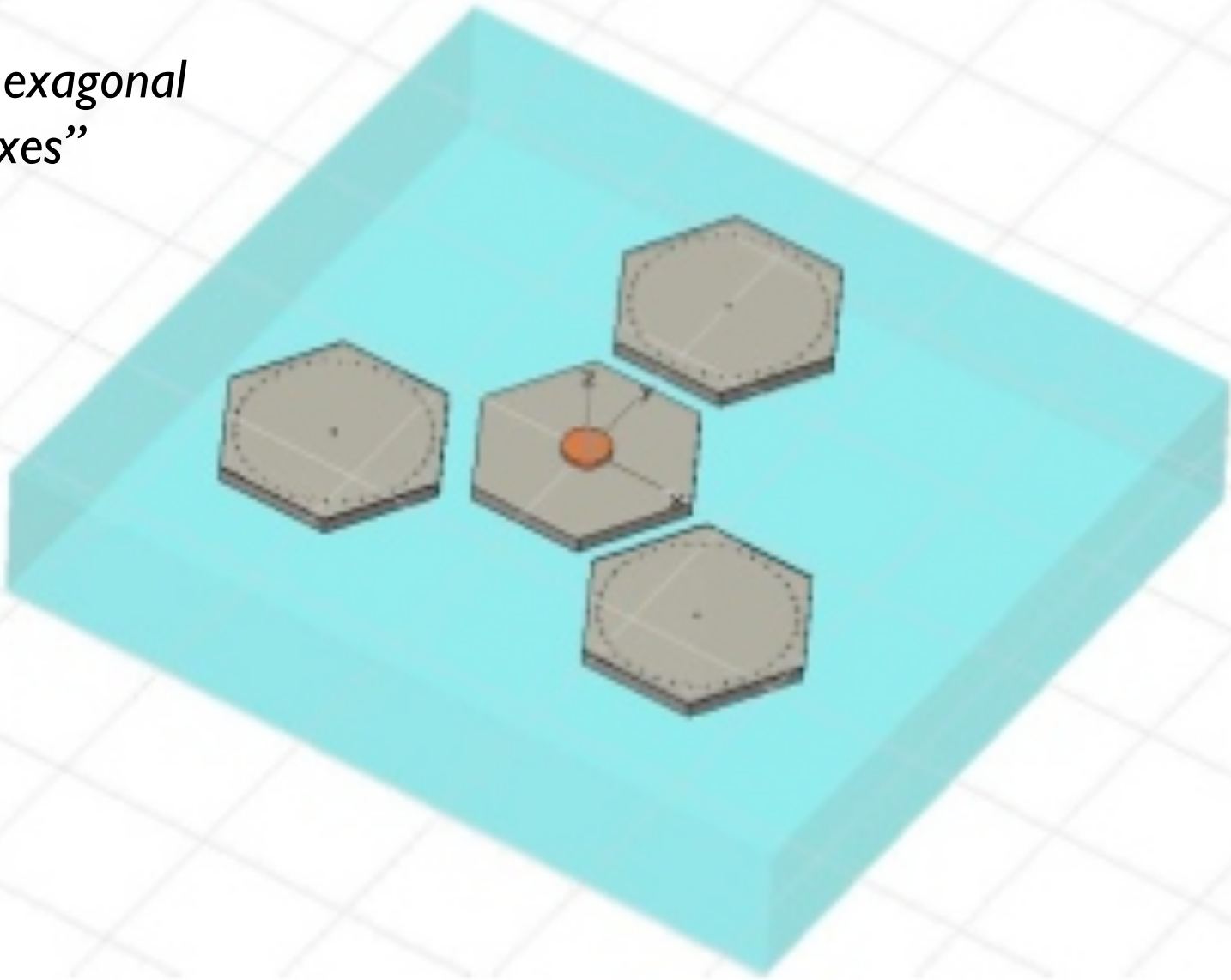


Figure 4: a) Scale drawing of the 90 MHz tri-helix, and b) simulated beam pattern of the tri-helix at 90 MHz with the antennas fed in phase.

STANCE development led by R. Bradley, NRAO

Fold to make hexagonal "pizza boxes"



STANCEs and ATHLETE loaded in Altair lander

We esimate one thousand STANCEs can be placed on moon in one lunar day by ATHLETE

G. Lee, JPL

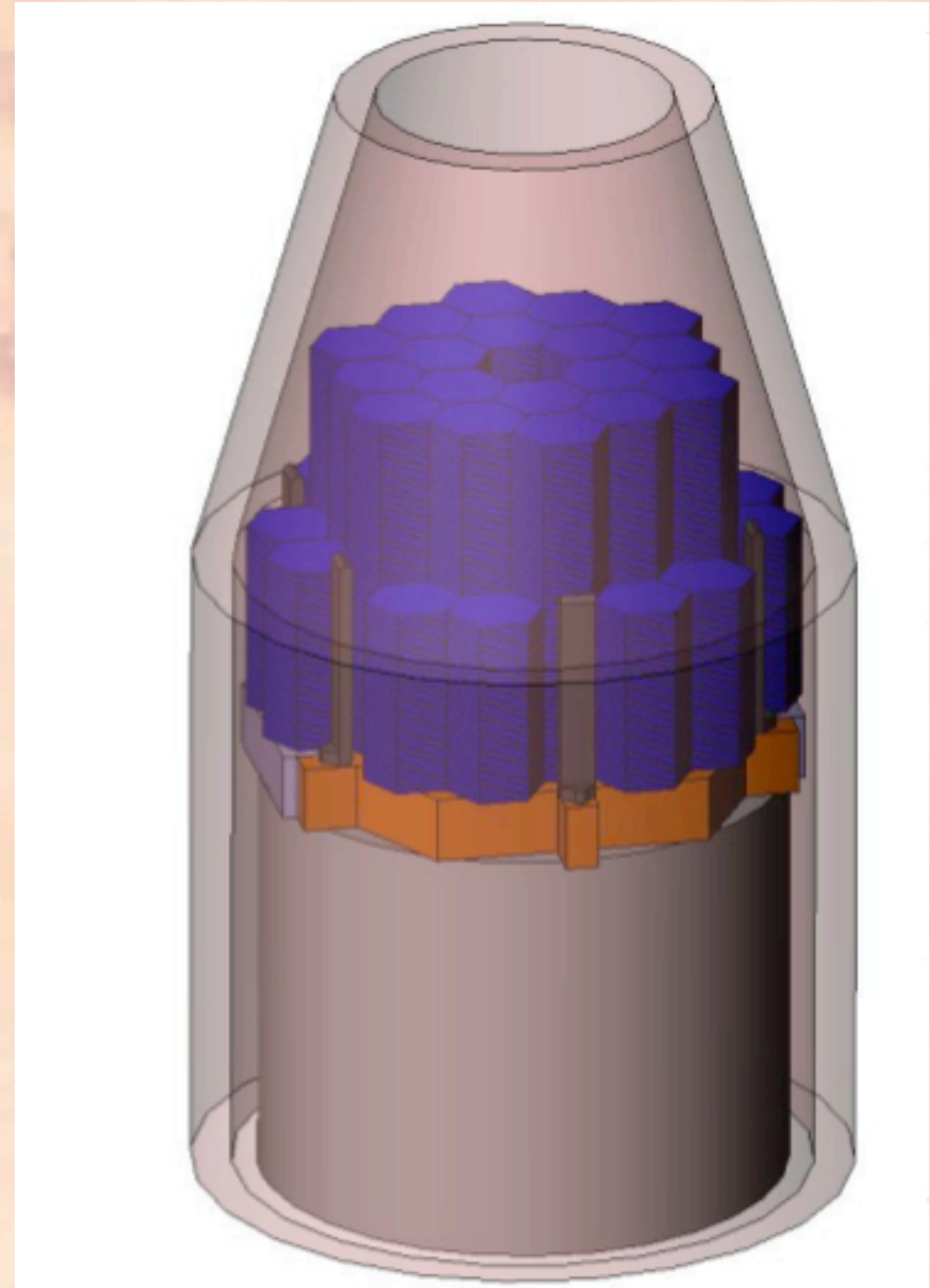
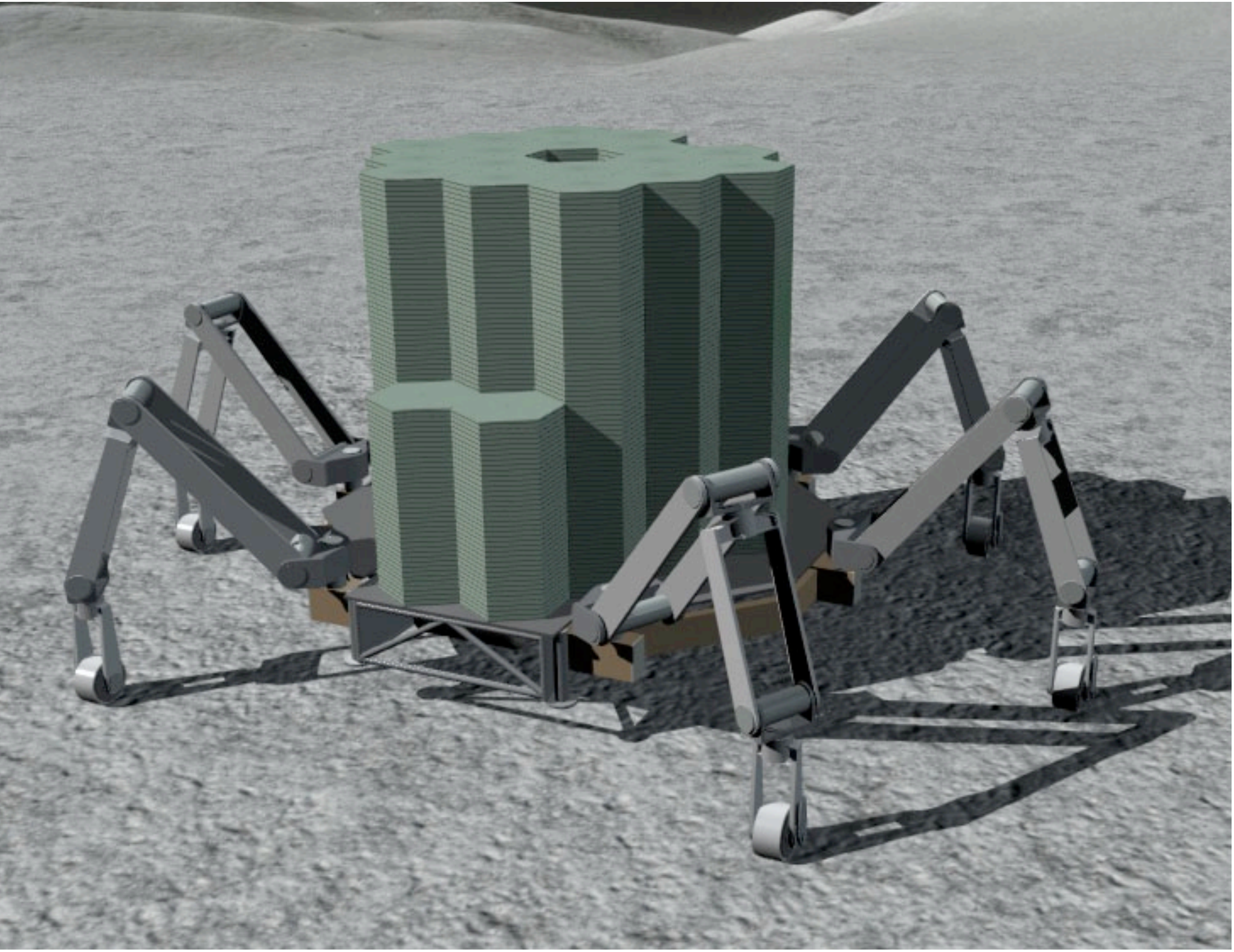
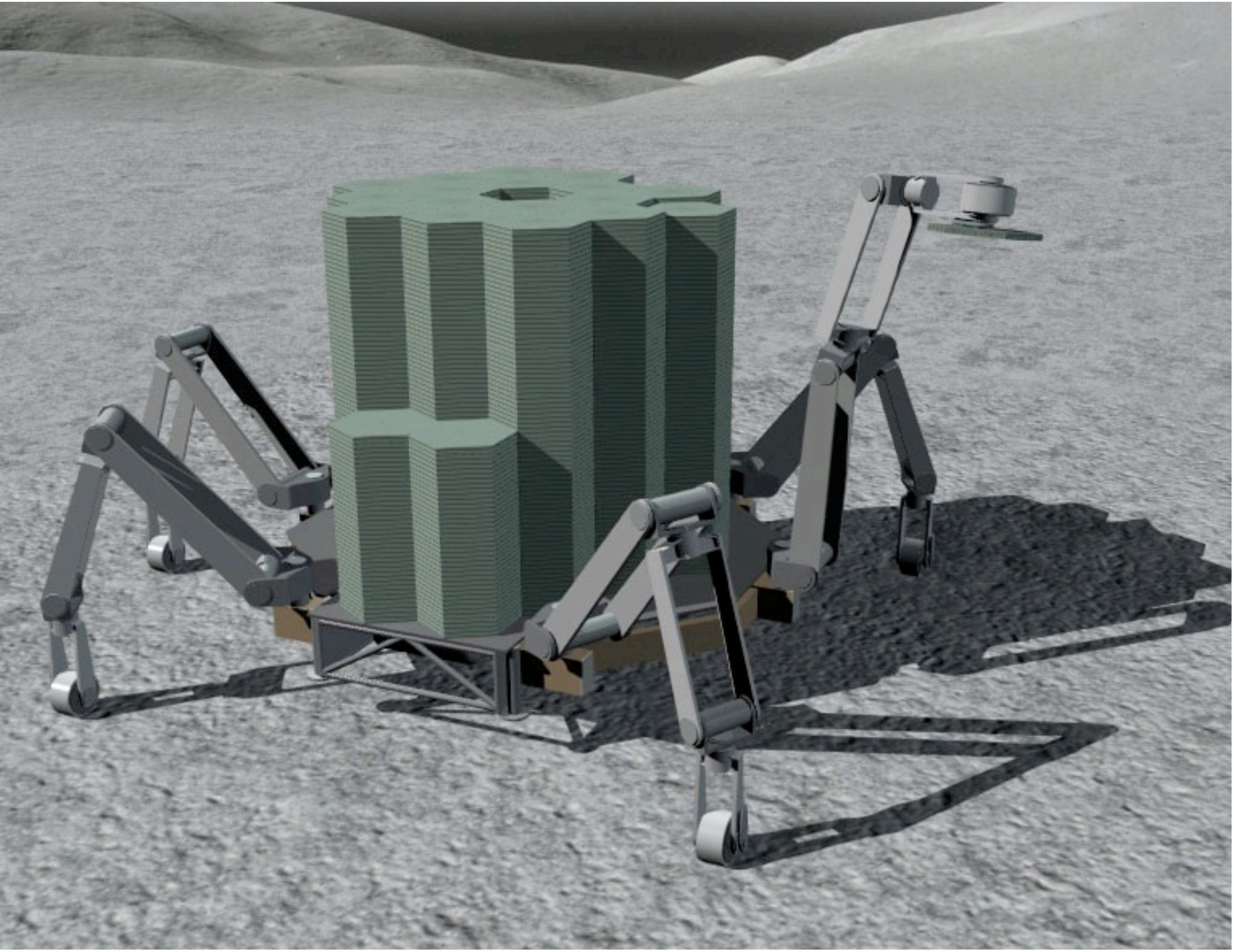
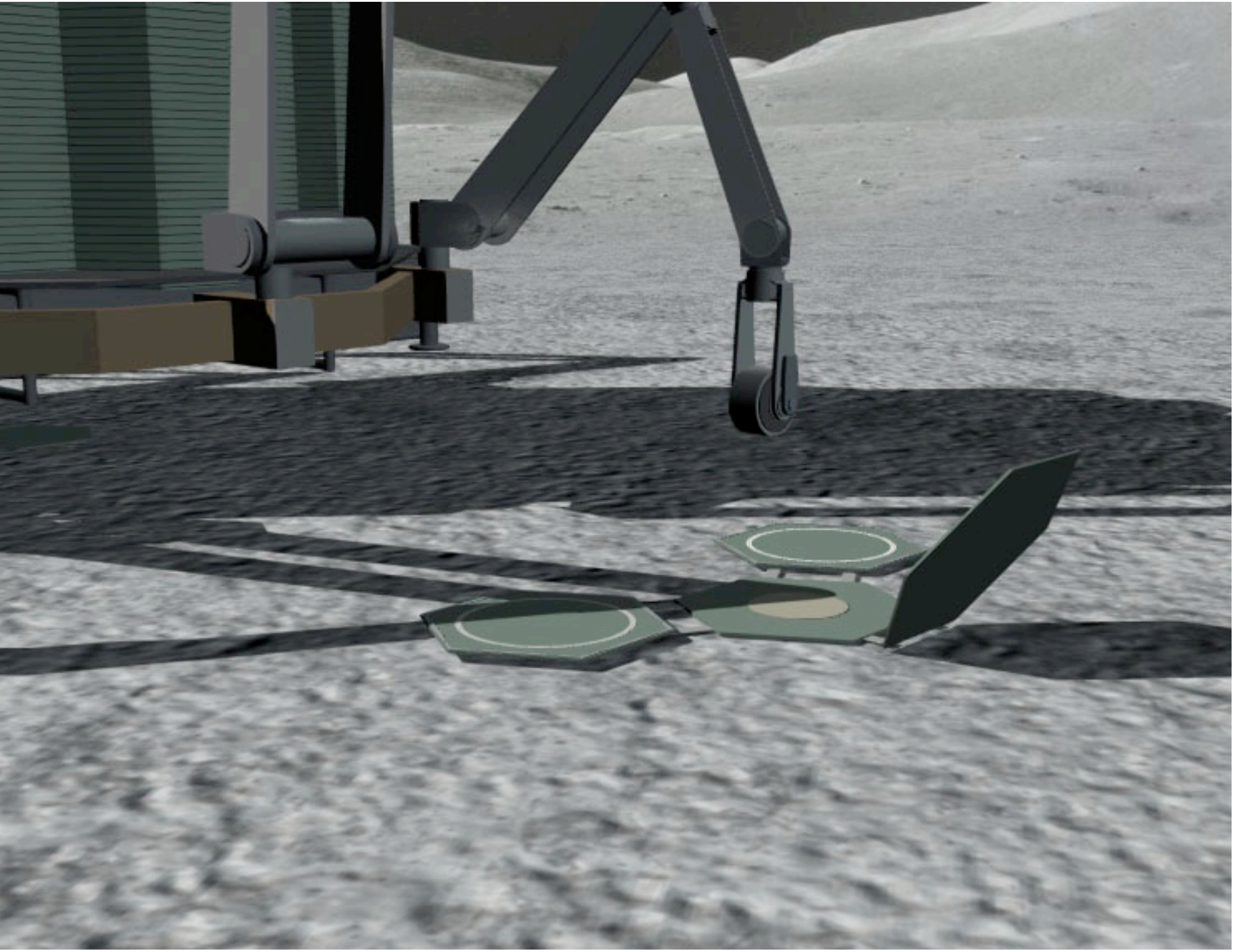
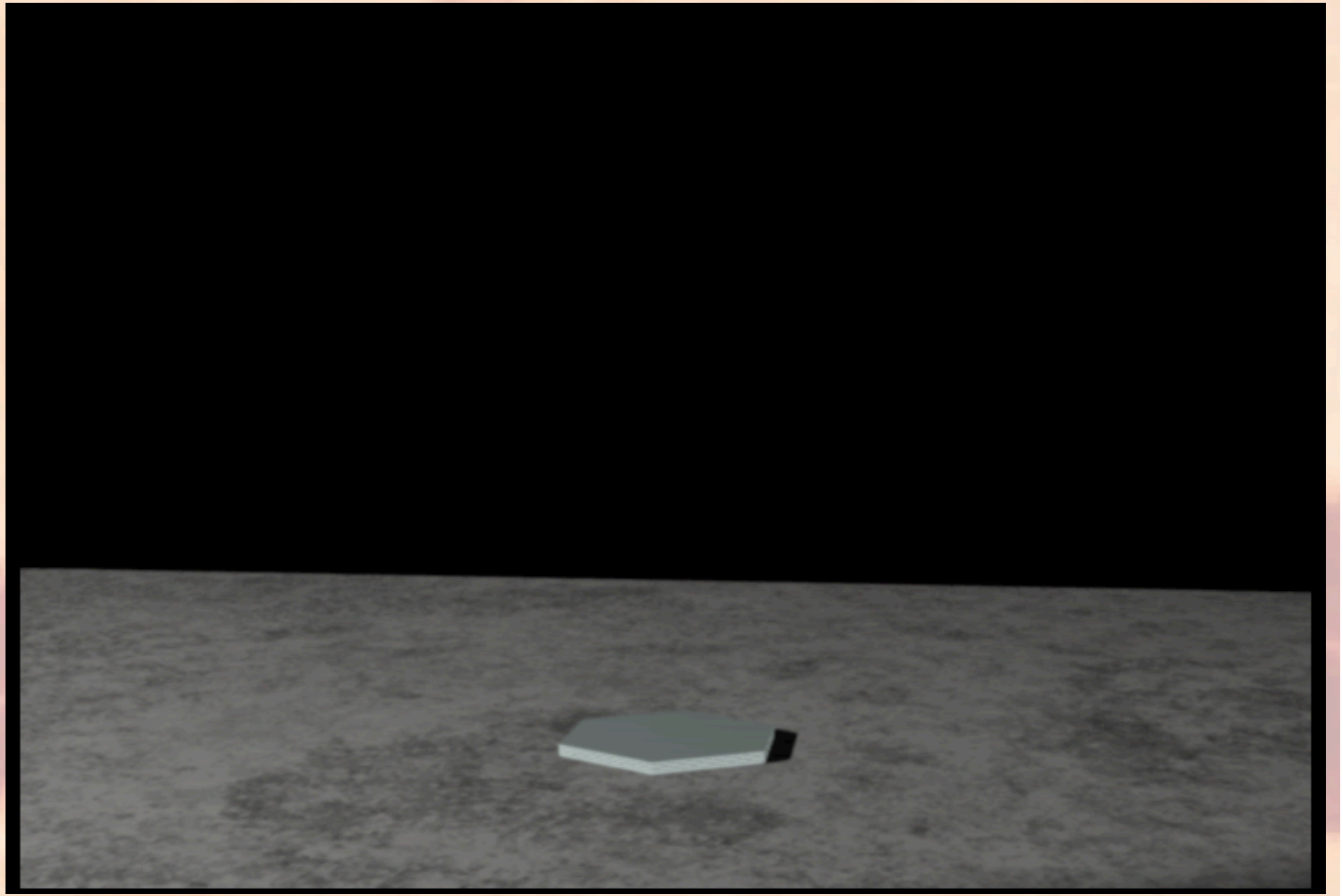


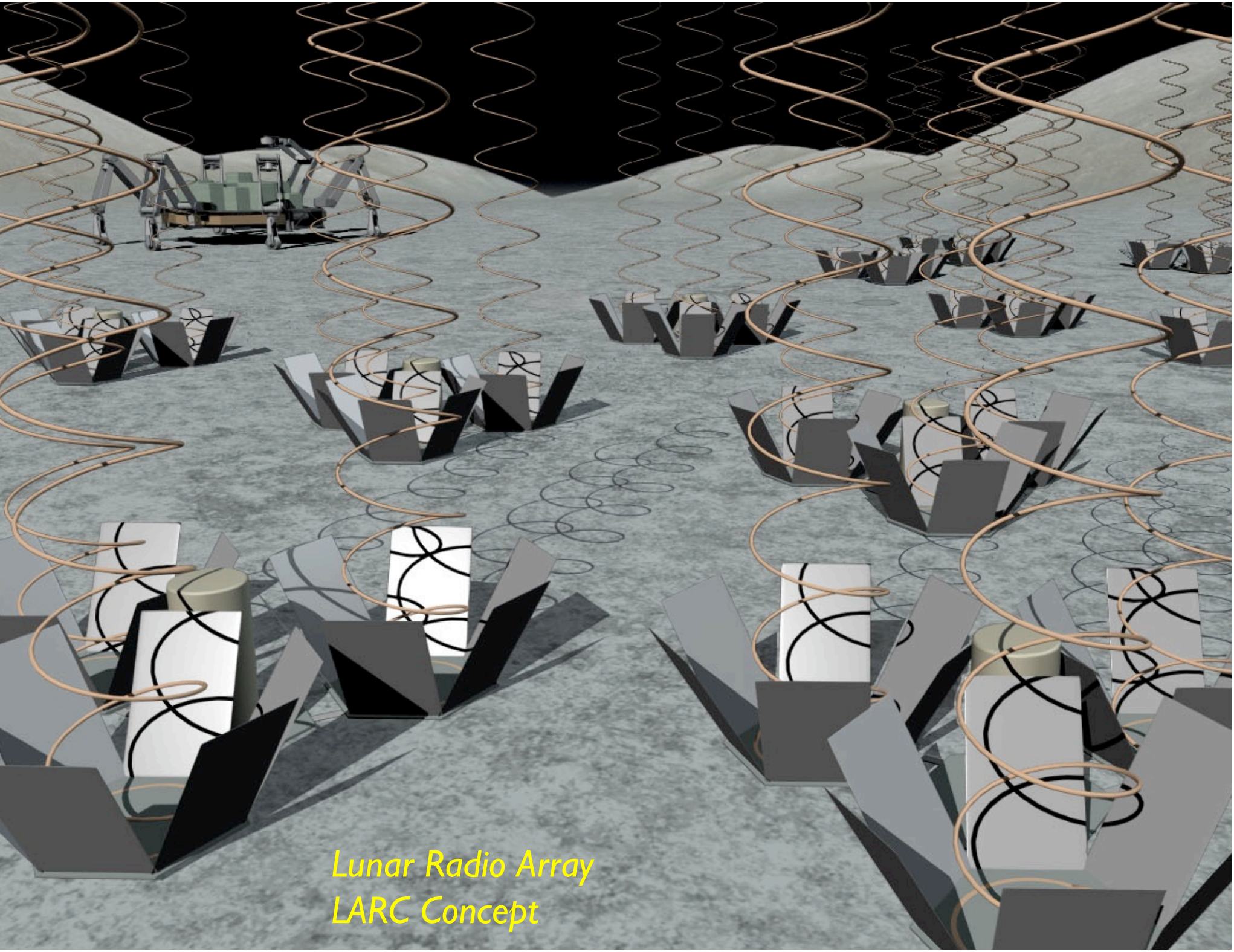
Figure 7. STANCE Packaging











Lunar Radio Array
LARC Concept

THE END

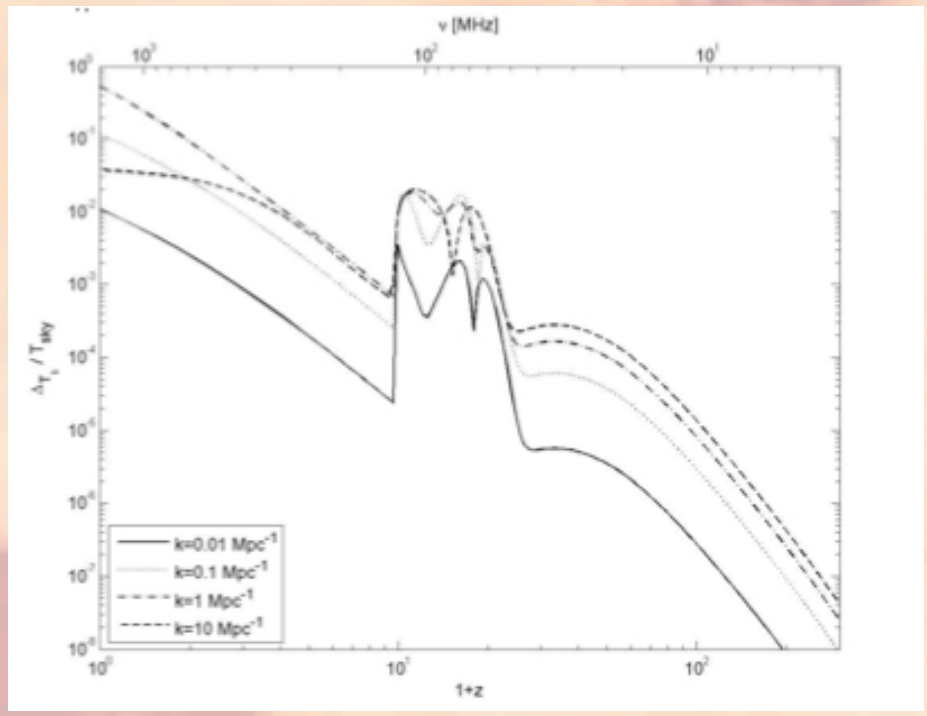
Other Elements of Science Program

- Cross-correlation with galaxy surveys
- Non-gaussianity of galaxy and star formation
- Non-gaussianity of some inflation models
- Separating “gastro-” physics from “real” physics
- Energy injection via dark matter decay

Challenge for all Science Goals:
Foreground Subtraction

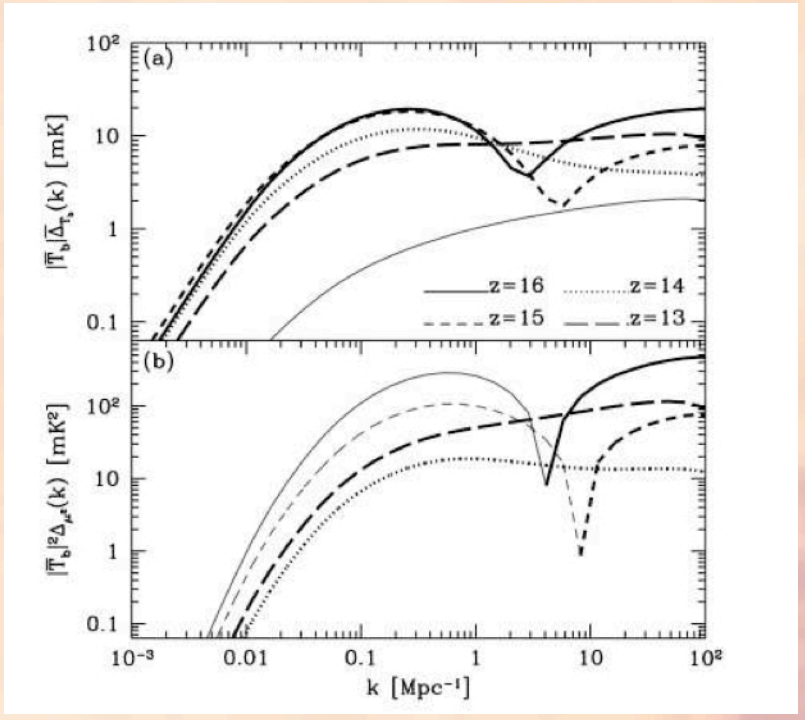
(Ambitious) Cosmology Targets

Reach for z=30 Dark Ages



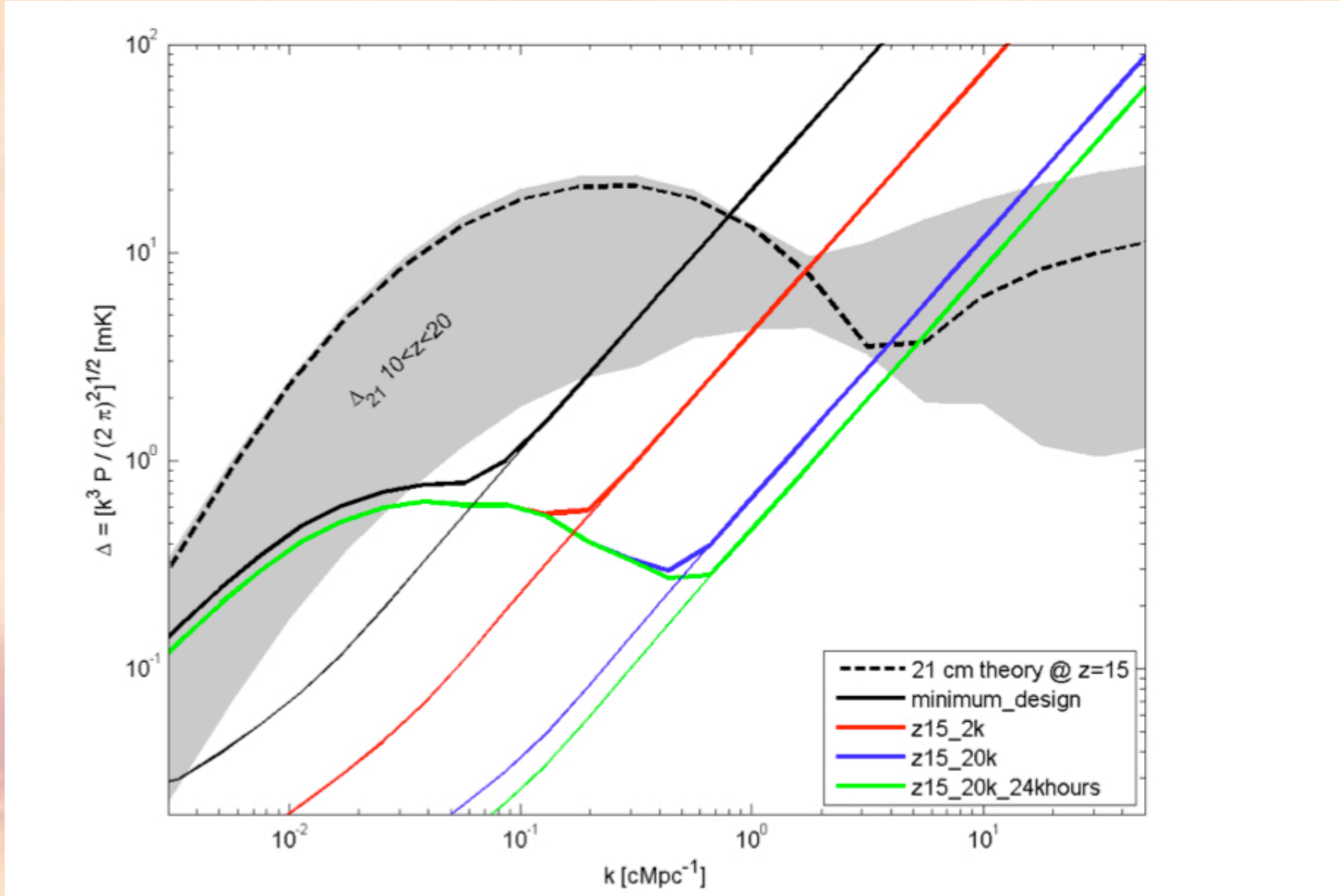
Pritchard & Loeb (2008), but divided by sky temperature

Elucidate reheating/reionization physics out to z=15 k=10



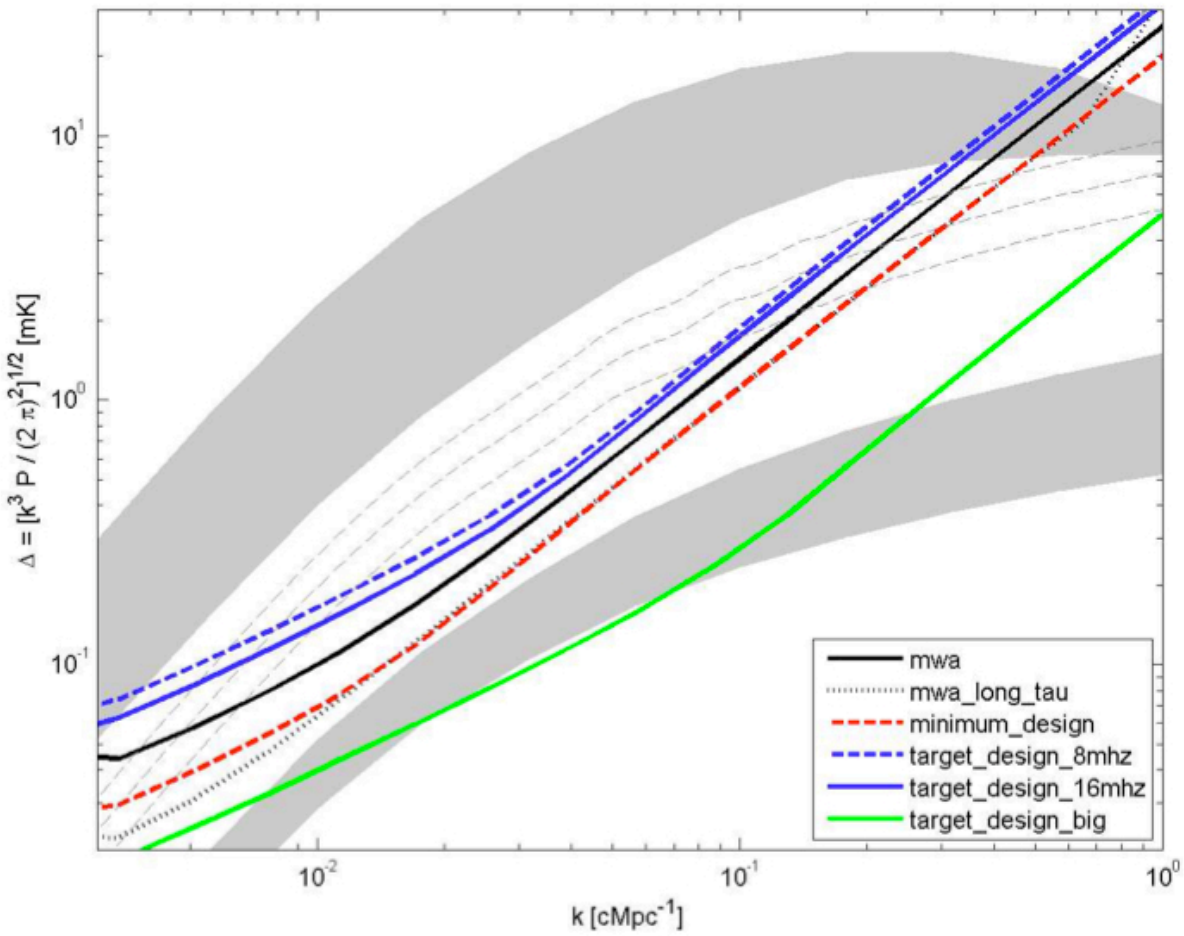
Pritchard & Furlanetto (2007)

Fiducial Arrays

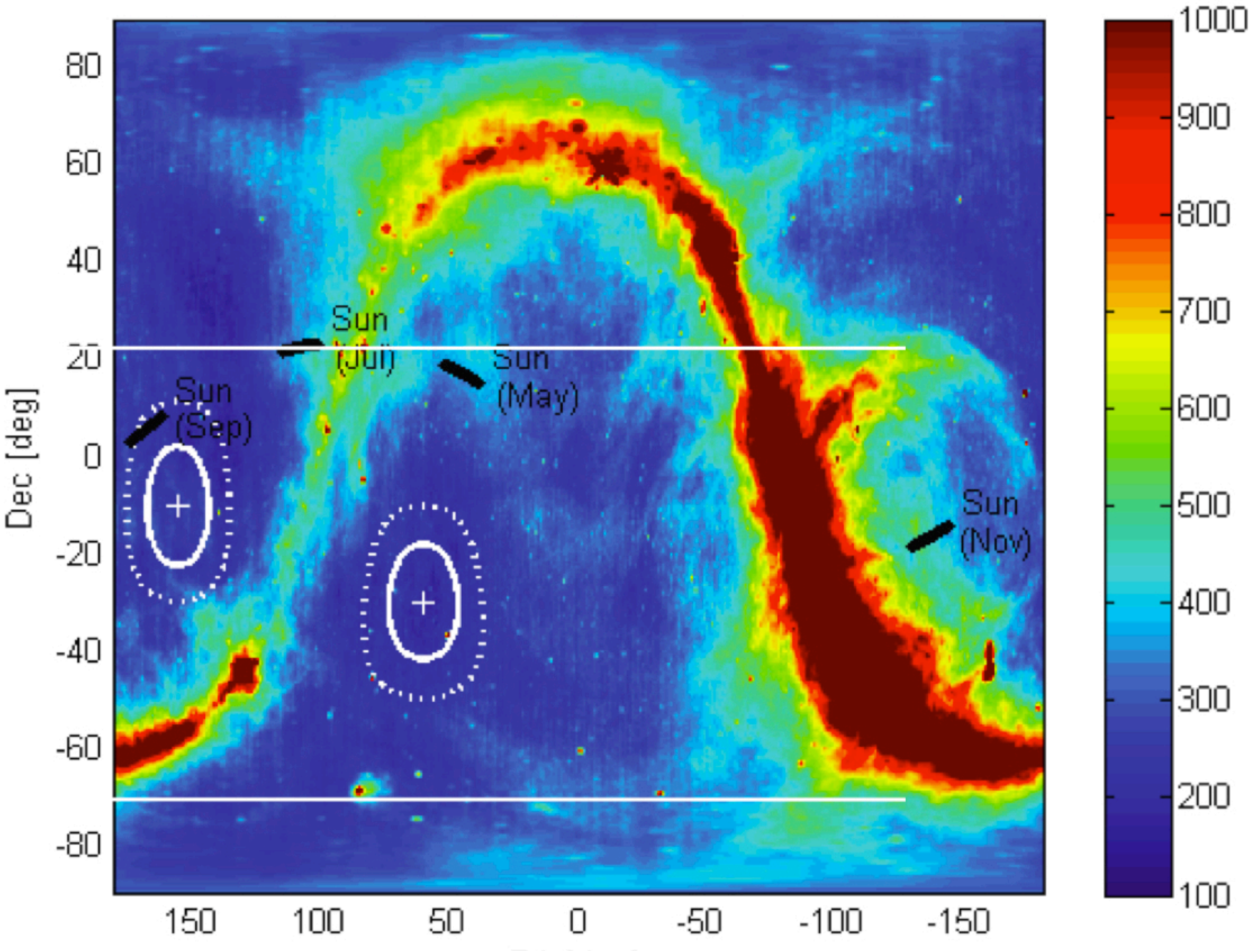


Calculation leading to BlackHole Design

Fiducial Arrays



Calculation leading to DarkAges Design


Sun
(Jul)
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50
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700
600
500
400
300
200
100

Data Transport and Array Commanding

Design	Data Rate (Gb/s)
Minimum	52.5
BlackHole	5,120
DarkAges	4,350

Table 3: Data transport requi

- Redundant pair of laser transmitters on each STANCE
- Modulator
- Laser pointing mechanism
- Transmit to central receiver at correlator
- Possible focussing element
- APD detectors (Lincoln Lab)
- Readout electronics to feed correlator
- Radio commanding system

Joel Villasenor will describe in more detail

Correlator

Frightening…but saved by ULP electronics

Design	N	Baselines N_b	Channel (kHz)	No. of Channels	Tera ops/sec	Power (W)
Minimum	410	83,845	25	320	31.0	0.177
BlackHole	20,000	2.00×10^8	25	640	165,000	830
DarkAges	17,000	1.44×10^8	25	640	120,000	600

Table 4: Correlator computation load and data rates.

Current baseline plan is to charge batteries during day and correlate during night while data are taken. Open trade is to store data on SSD's and correlate during day.

Charles Lawrence will describe in more detail

Post-Correlation Data Rates

Small array size and slow rotation of Moon allow significant averaging: Adopt 250 kHz channels and 15 mins (!). If each complex visibility (4 polarization products) is 32 bytes then

Minimum: 380 kB/sec
BlackHole: 1.8 GB/sec
DarkAges: 1.3 GB/sec

Visibility average would further reduce data rate.

Deployment

Not yet addressed – study to be carried out in February led by J. Hoffman

Siting Considerations

(J. Hoffman memo)

- Earth's RFI => at least 300 km from South Pole Base (RFI from Base??). To complement DALI, we will focus on South Pole access option.

- Sky viewing angle – cold spot for EoR/DA. Secondary science may be severely impacted by this.

- Large flat area with access from South Pole Base – await LRO maps

- Compatibility with other Exploration objectives

- Thermal requirements, power systems, and communications