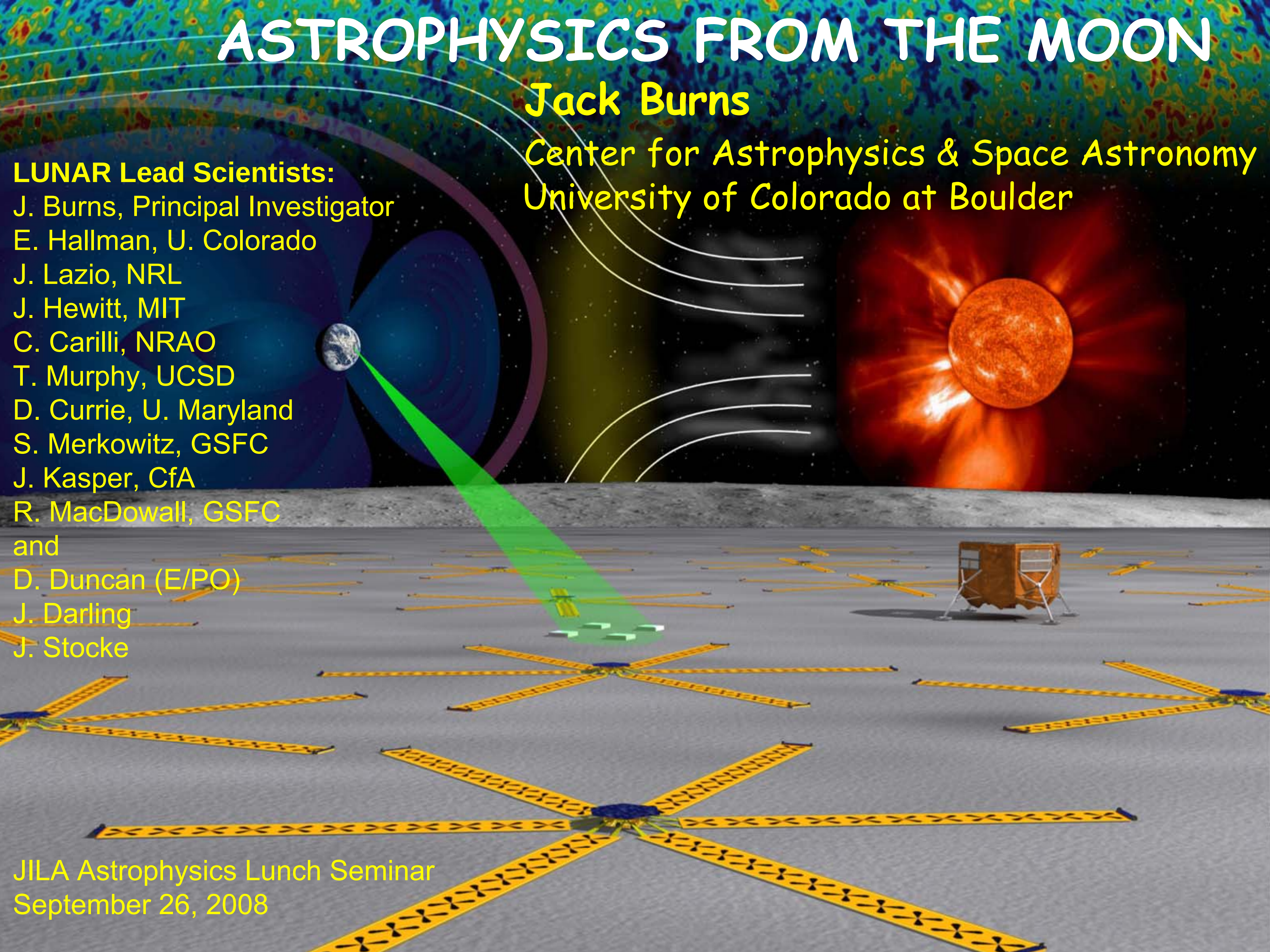


ASTROPHYSICS FROM THE MOON

Jack Burns

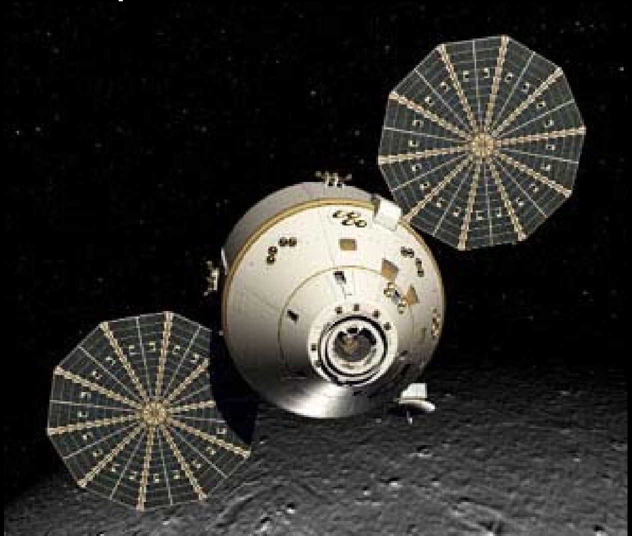
Center for Astrophysics & Space Astronomy
University of Colorado at Boulder

LUNAR Lead Scientists:
J. Burns, Principal Investigator
E. Hallman, U. Colorado
J. Lazio, NRL
J. Hewitt, MIT
C. Carilli, NRAO
T. Murphy, UCSD
D. Currie, U. Maryland
S. Merkowitz, GSFC
J. Kasper, CfA
R. MacDowall, GSFC
and
D. Duncan (E/PO)
J. Darling
J. Stocke

JILA Astrophysics Lunch Seminar
September 26, 2008

National Space Exploration Policy, Authorized by Congress

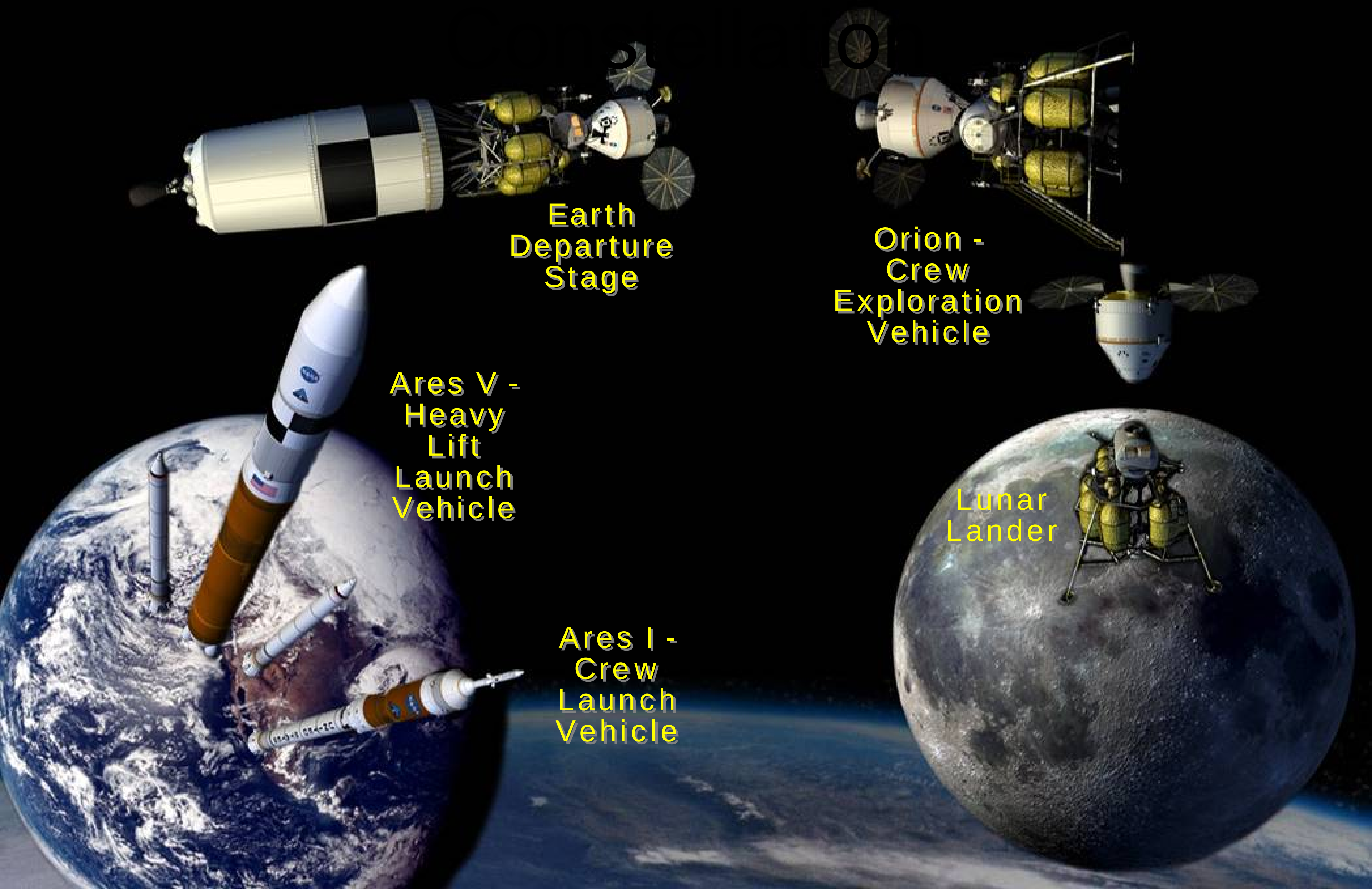
- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle (Orion) no later than 2014
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration



NASA Authorization Act of 2005

The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations.

Components of the Constellation Program



Earth Departure Stage

Orion - Crew Exploration Vehicle

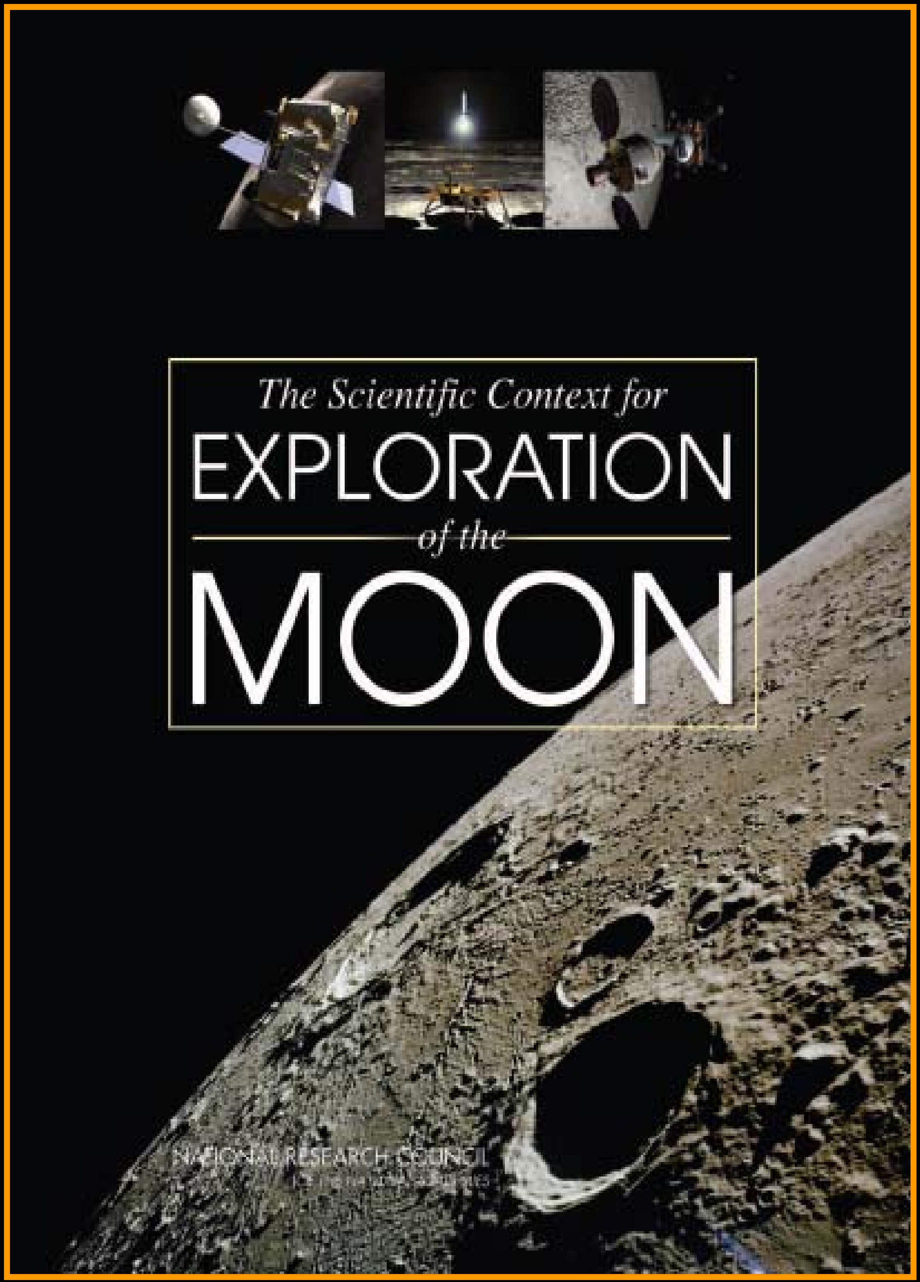
Ares V - Heavy Lift Launch Vehicle

Lunar Lander

Ares I - Crew Launch Vehicle

Exploring the Cosmos From the Moon

Comments from NRC Study (2007)



The Scientific Context for

EXPLORATION

of the

MOON

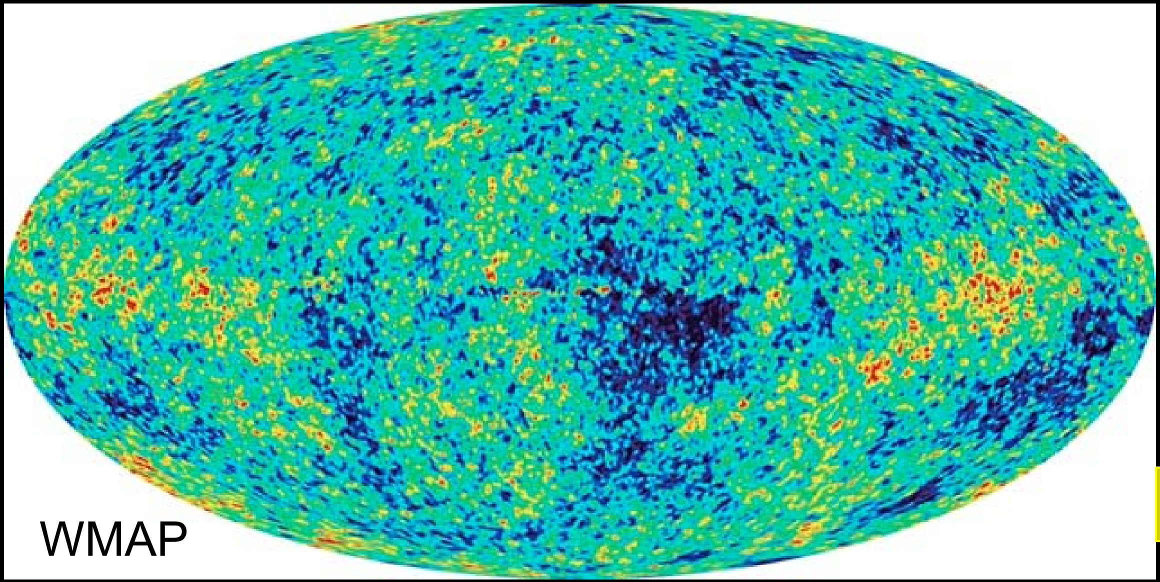
NATIONAL RESEARCH COUNCIL

- “Extraordinary radio-quiet of lunar farside” would be a “powerful tool to investigate the *Dark Ages* of the Universe … in highly redshifted signals from neutral hydrogen”.
- Imperative to subject Einstein’s model of gravity to the utmost scrutiny. Lunar laser ranging is on the frontline of such tests.

The Universe In Transition

From the CMB

400,000 yrs after Big Bang



Recombination (400,000 yrs)

The Dark Ages

Reionization & 1st stars (~10^9 yrs)

To

Clusters Of Galaxies

Today

HST

TIME Magazine cover story, 9/2006

Light From a Dark Age

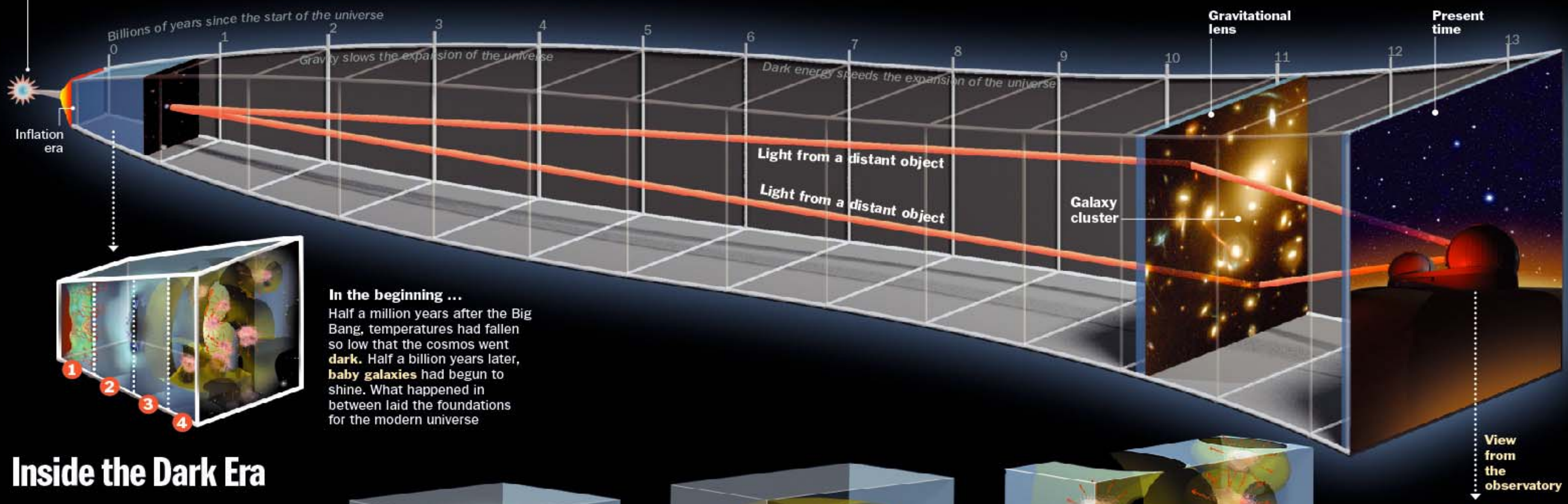
How the universe grew from dark soup to twinkling galaxies

Looking for the beginning of time ...

Big Bang About 13.7 billion years ago, the universe burst into existence, creating both **space** and **time**

... 13.4 billion years later

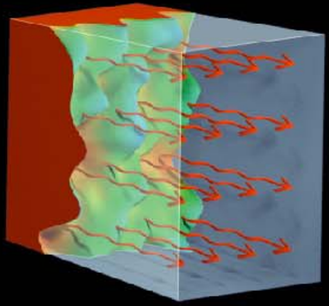
Albert Einstein suggested that **gravity** from a massive forergound object could distort and magnify background objects. By looking through a **cluster of galaxies,** astronomers have now found the magnified images of much more distant galaxies

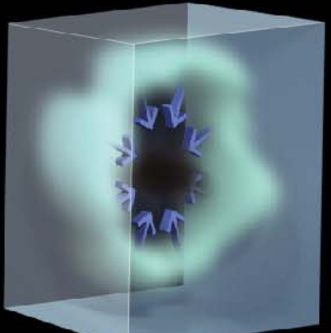


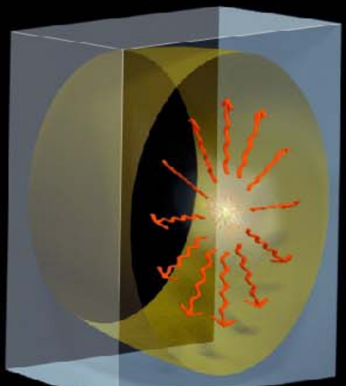
In the beginning ...

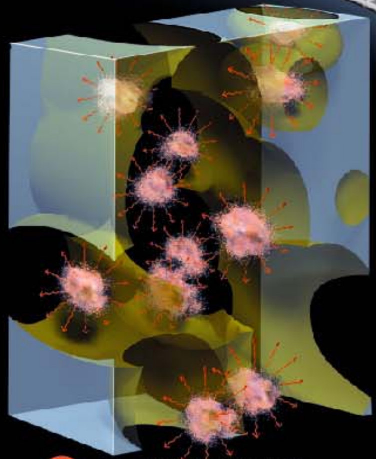
Half a million years after the Big Bang, temperatures had fallen so low that the cosmos went **dark.** Half a billion years later, **baby galaxies** had begun to shine. What happened in between laid the foundations for the modern universe

Inside the Dark Era









① THE DARK AGES BEGIN

When the cosmos is about **400,000 years** old, it has cooled to about the temperature of the surface of the Sun, allowing subatomic particles to combine for the first time into **atoms.** The last burst of light from the Big Bang shines forth at this time; it is still detectable today in the form of a faint whisper of **microwaves** streaming in from all directions in space. The discovery of those microwaves in 1964 confirmed the existence of the Big Bang

② DARK MATTER

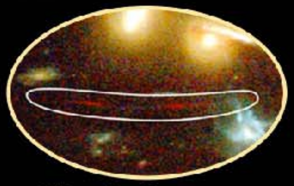
Far more abundant than ordinary atoms, **dark-matter particles** were spread unevenly through the cosmos; areas of higher concentration drew in **hydrogen** and **helium gas,** gradually forming knots dense enough to burst into thermonuclear flame, forming the **first stars**

③ FIRST STARS

The earliest stars were extremely large and dense, weighing in at 20 to 100 times the mass of the Sun, and more. The crushing pressures at their cores made them burn through their nuclear fuel in only a million years or so, and caused them to spew out such intense radiation that it kept other stars from forming. The first **"galaxies"** may have consisted of clouds of hydrogen and helium surrounding just one **mega-star**

④ END OF THE DARK AGES

The death of the megastars triggered the formation of normal stars, creating the first normal-looking **dwarf galaxies.** Their radiation in turn burned through the remaining shrouds of hydrogen, bringing the dark ages to a close.

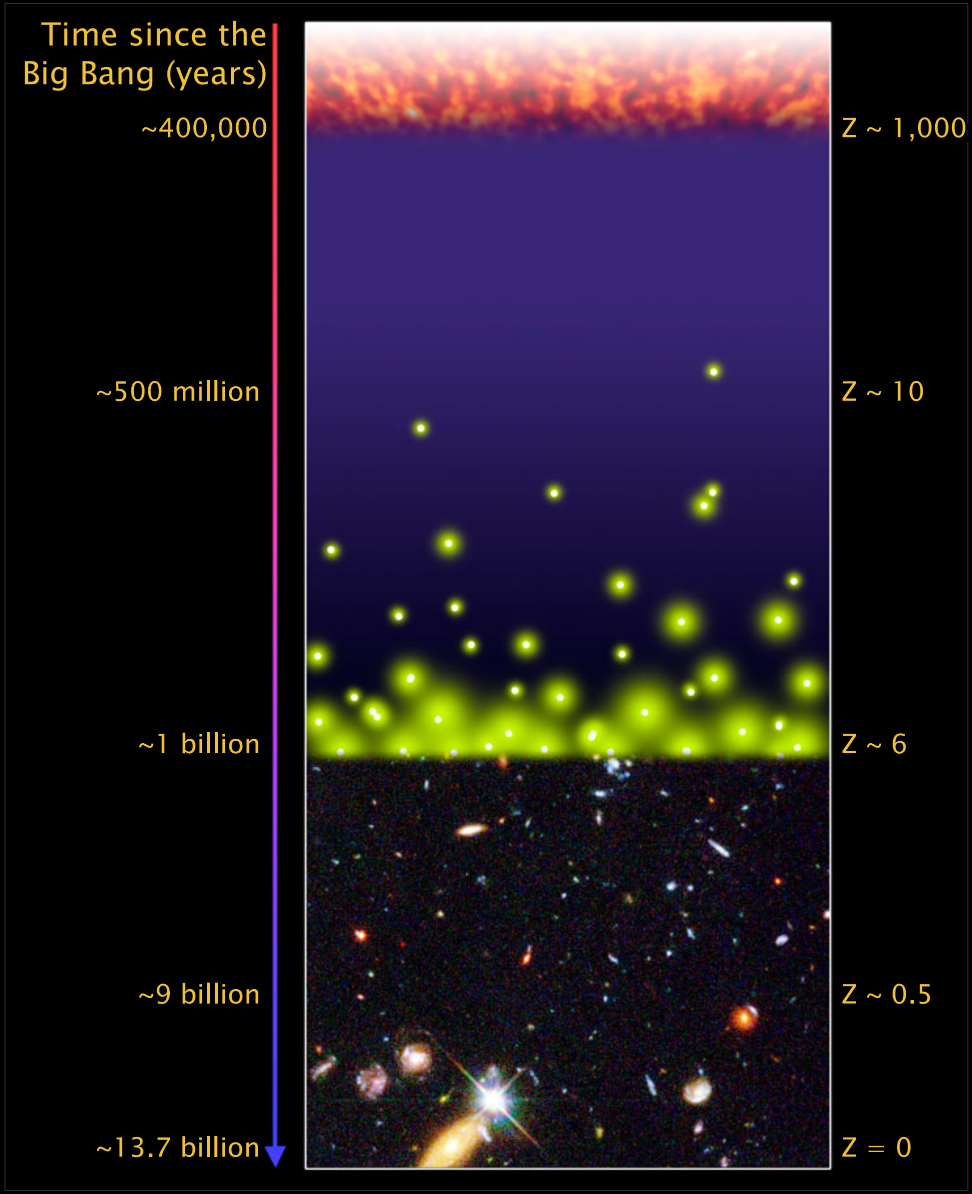


What they're really seeing

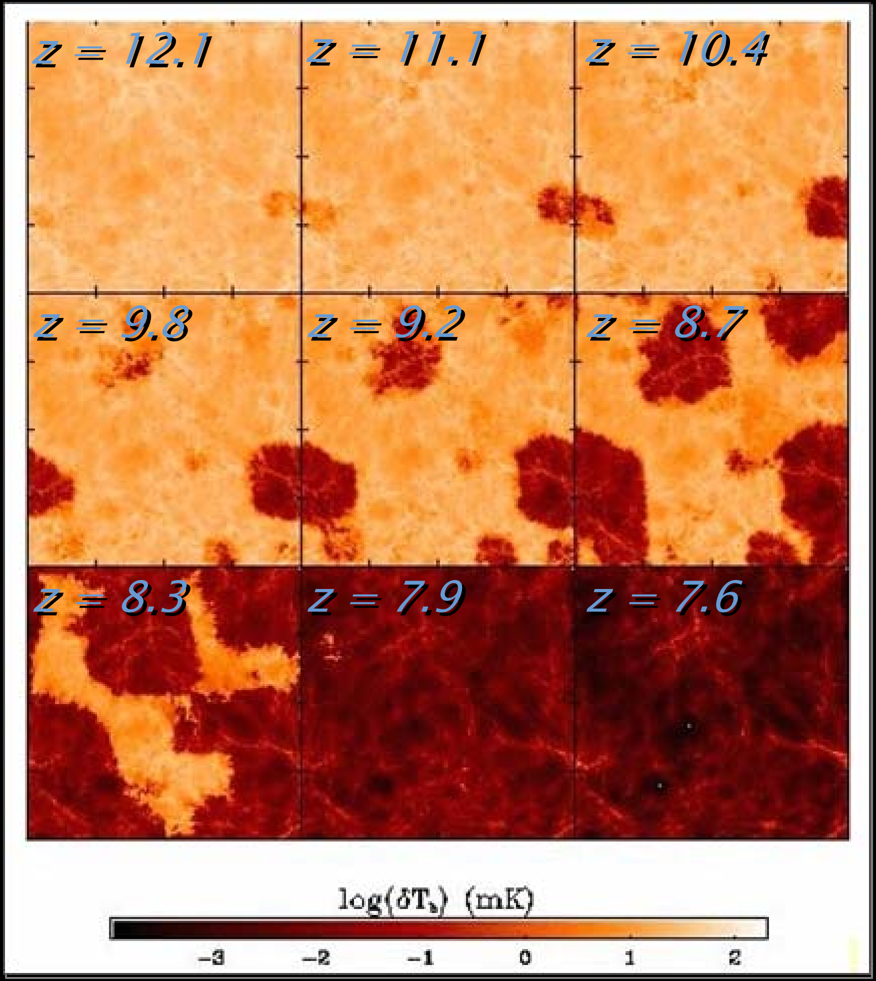
Richard Ellis of Caltech has found distant galaxies warped into odd, elongated shapes, as though they were being glimpsed through a cosmic funhouse mirrror. The light from these galaxies could ordinarily never be glimpsed through existing telescopes

TIME Graphic by Joe Lertola
Sources: TKTKTK

Reionization and the Dark Ages

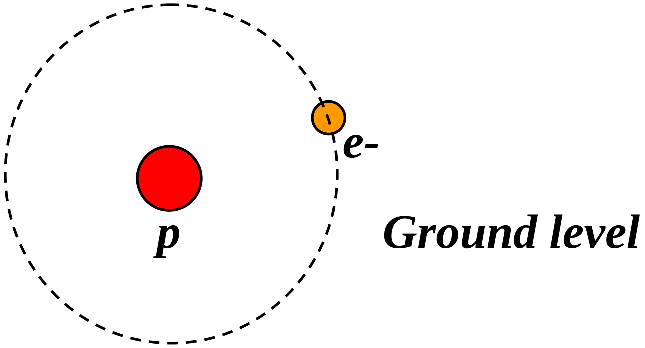


Reionization



Fluctuations are at about 10 mK

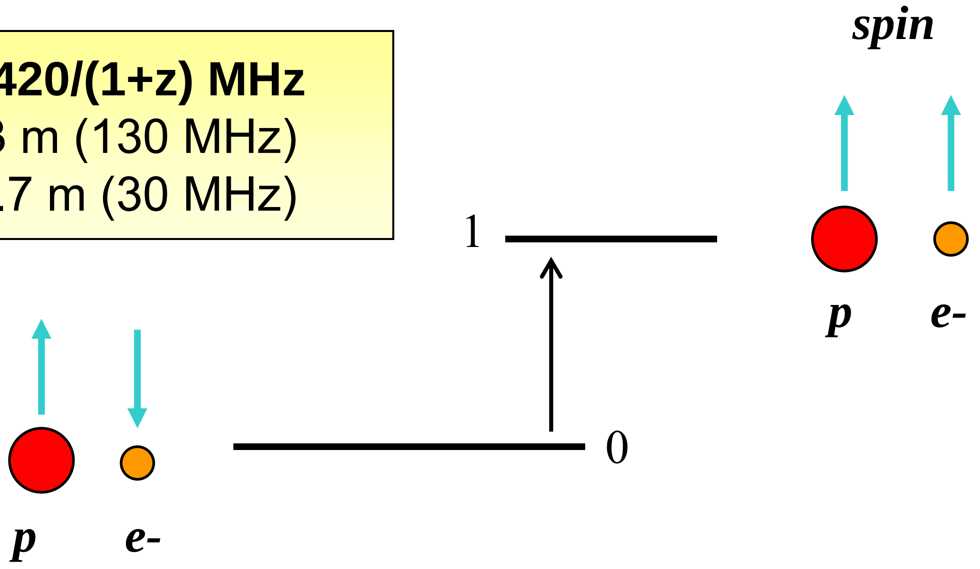
Hydrogen



excitation rate= (atomic collisions)+(radiative coupling to CMB)

Couple T_s ***to*** T_k ***Couples*** T_s ***to*** T_{CMB}

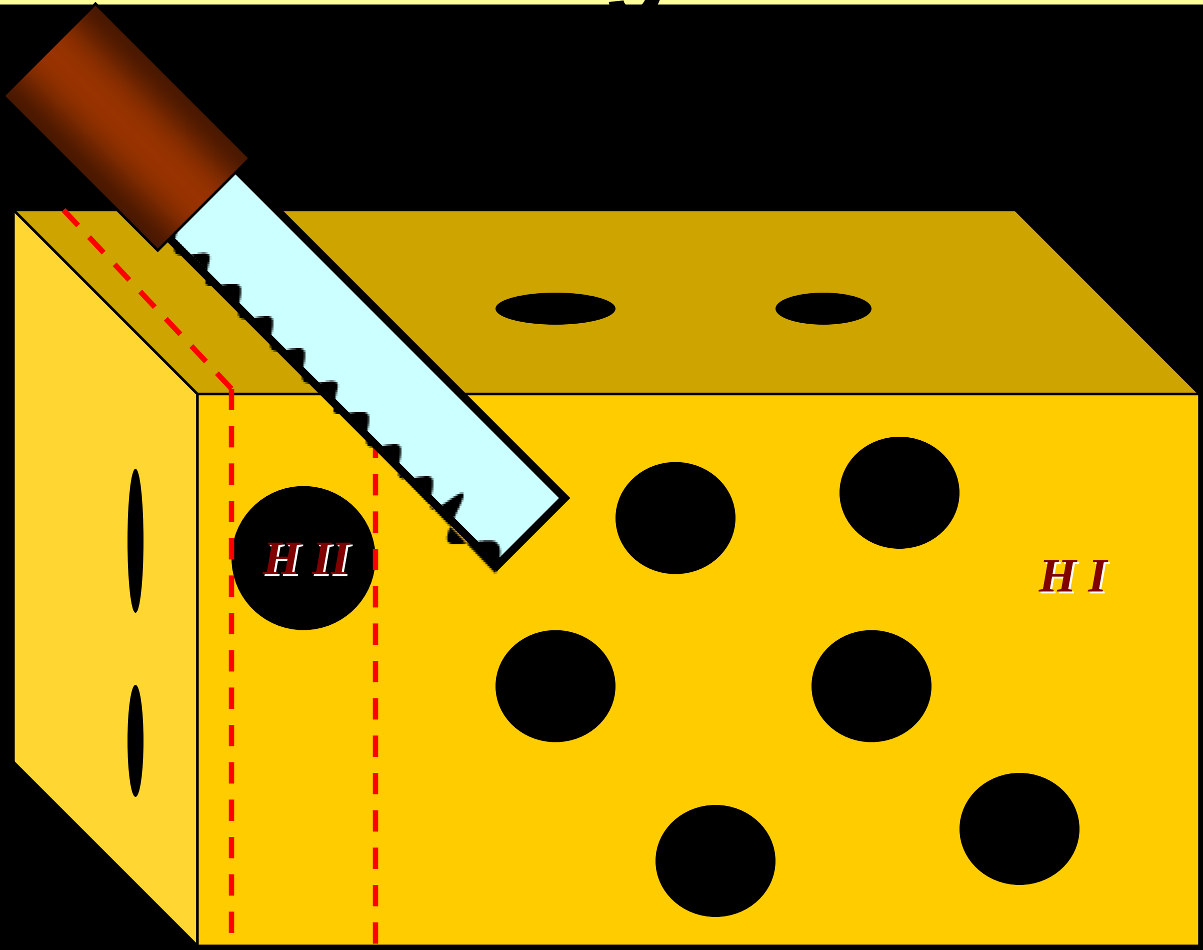
21 (1+z) cm = 1420/(1+z) MHz
At z=10, λ = 2.3 m (130 MHz)
At z=50, λ = 10.7 m (30 MHz)



$\mathbf{n_1/n_0 = g_1/g_0 \exp(-T_*/T_s)}$ where $g_1/g_0=3$, $T_*=0.068$ K

Predicted by Van de Hulst in 1944; Observed by Ewen &Purcell in 1951 at Harvard

21cm Tomography of Ionized Bubbles During Reionization is like Slicing Swiss Cheese



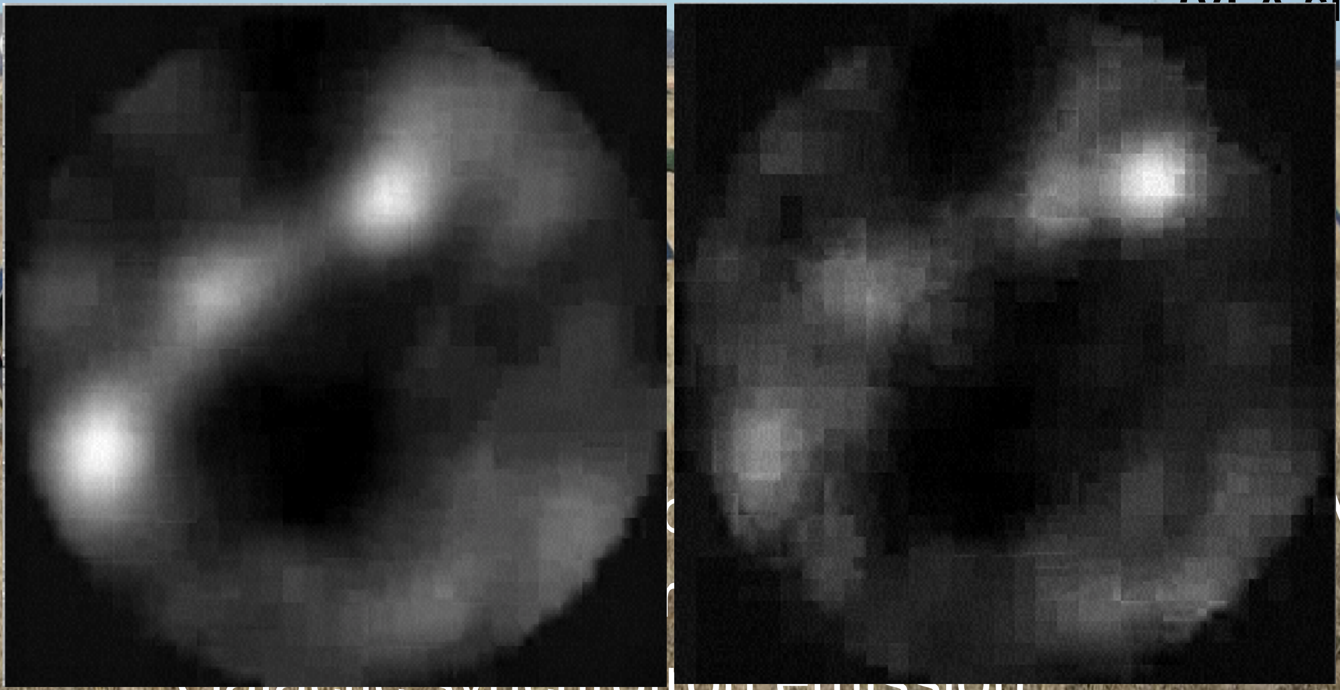
Observed wavelength ⇔ distance

21cm (1+z)

(Loeb, 2006, astro-ph/063360)

Primary Challenge for Earth Arrays: Foregrounds

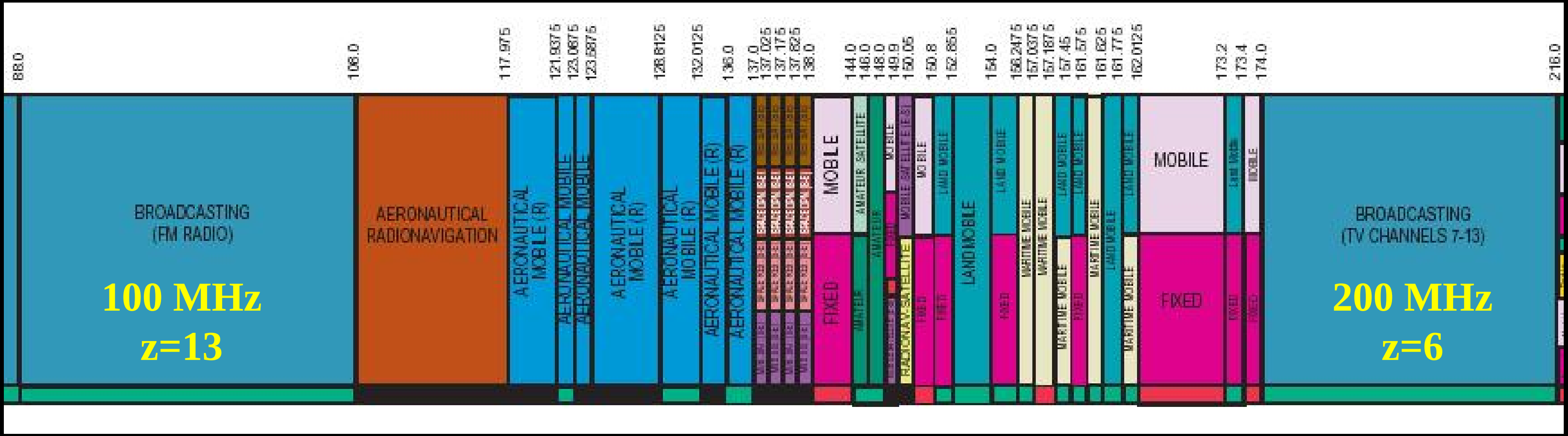
Long Wavelength Array (VLA site in NM)



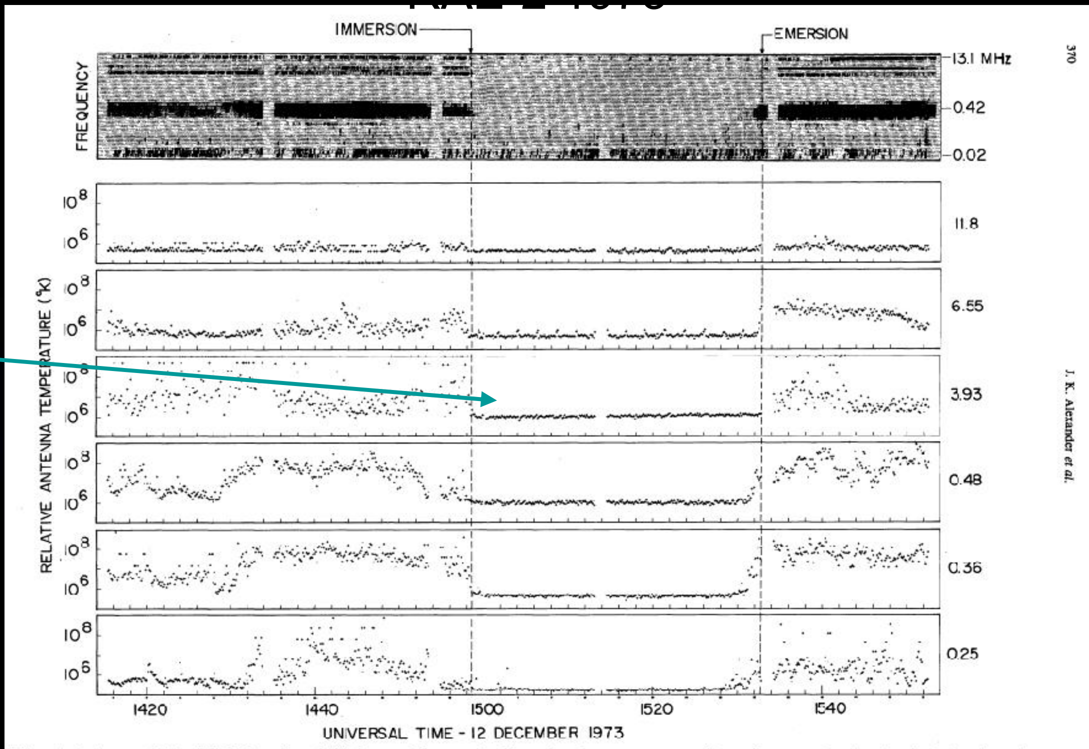
- Galactic synchrotron emission
- Extragalactic: radio sources

(*Di-Matteo et al. 2004*)

Lunar Advantage: No Interference



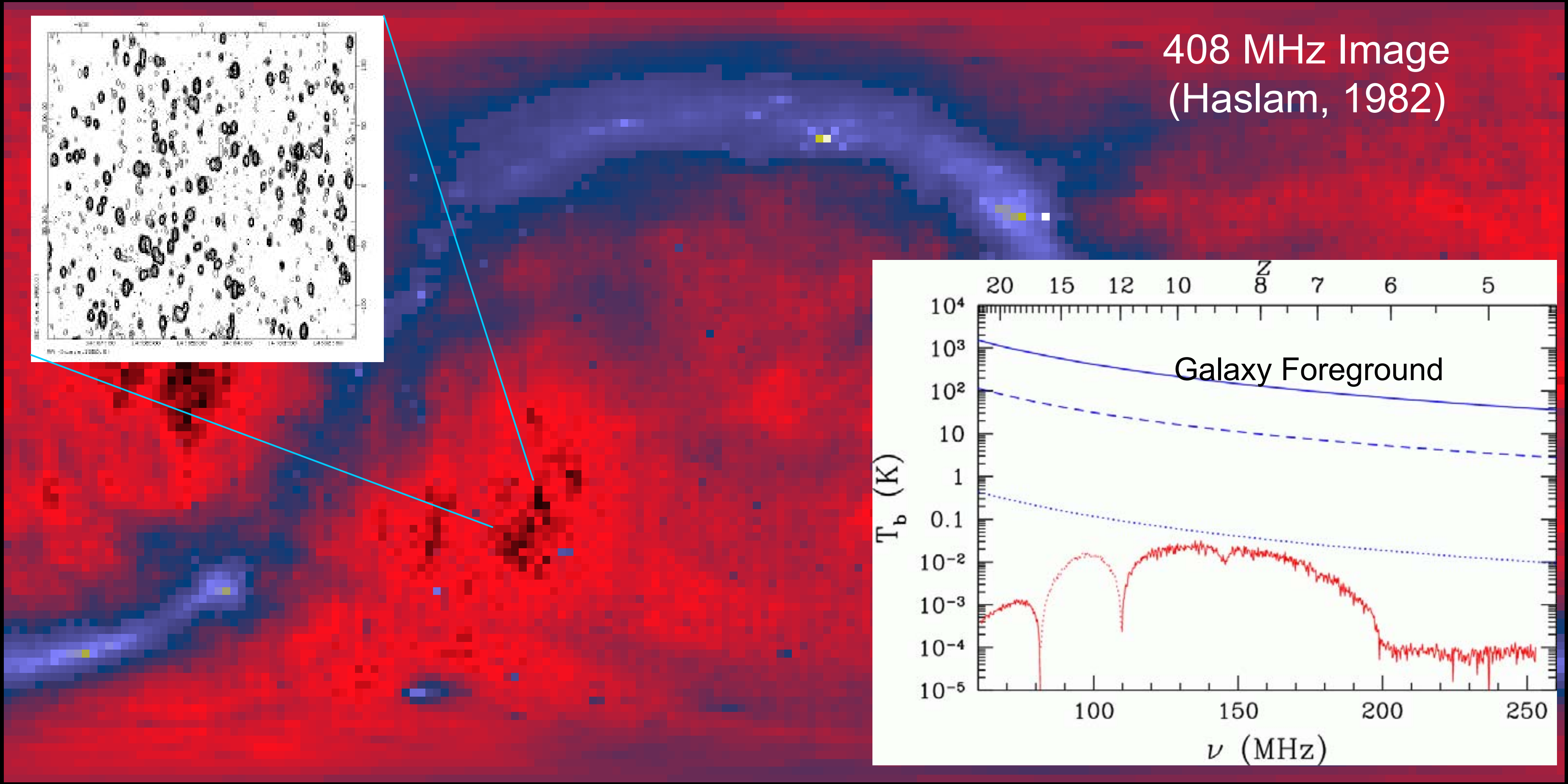
Destination: Moon!



5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time ations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses erved every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver the burst receiver are tuned to the same frequency

Remaining challenge: Low Frequency Foreground

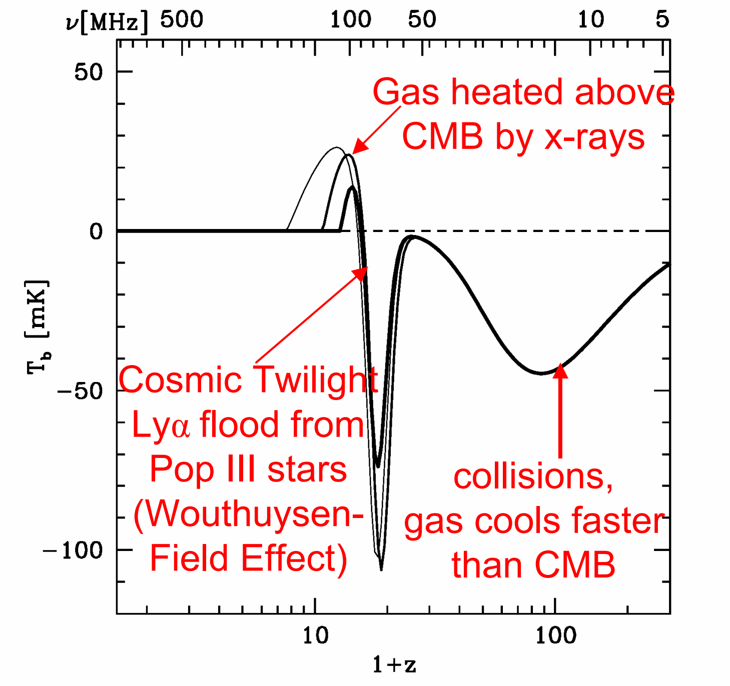
- Coldest regions: $T = 100\ (\nu/200\ \mathrm{MHz})^{-2.7}$ K
- Highly ‘confused’: 3 sources/arcmin^2 with $S_{0.2} > 0.1$ mJy



408 MHz Image
(Haslam, 1982)

Solution: fitting in the spectral domain

The Global (sky-averaged) HI Signal

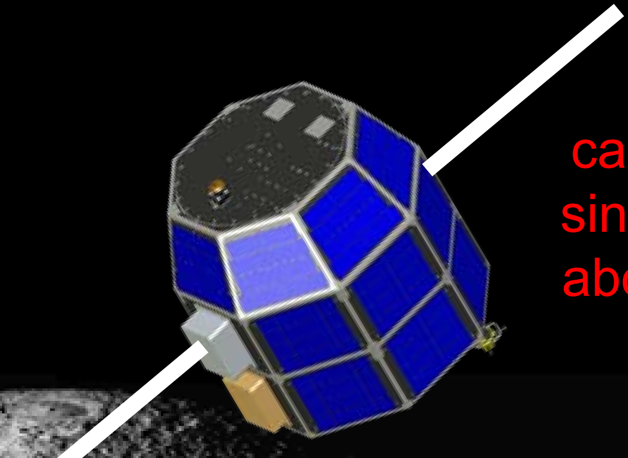


Gas heated above CMB by x-rays

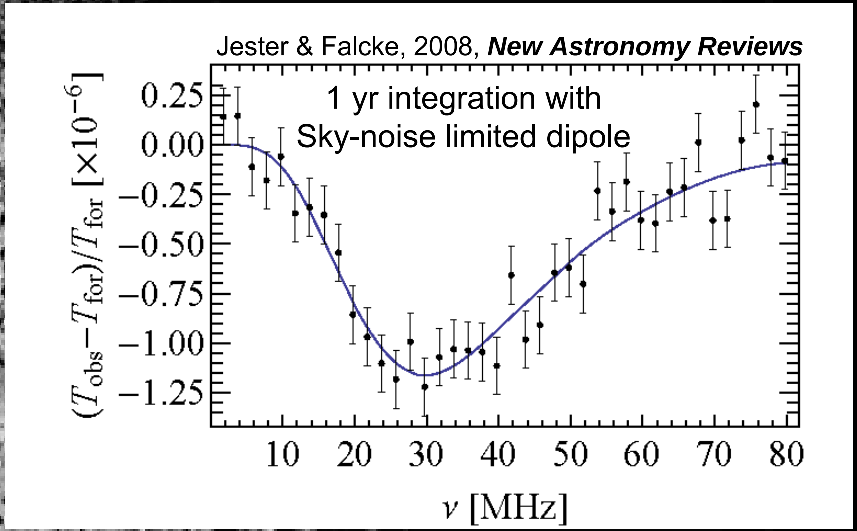
Cosmic Twilight Lyα flood from Pop III stars (Wouthuysen-Field Effect)

collisions, gas cools faster than CMB

LADEE = Lunar Atmosphere & Dust Environmental Explorer



Global signal can be detected by single dipole in orbit above lunar farside!



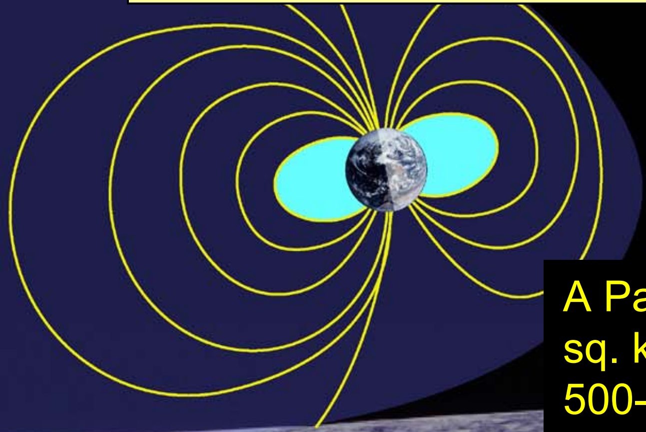
Jester & Falcke, 2008, ***New Astronomy Reviews***

1 yr integration with Sky-noise limited dipole

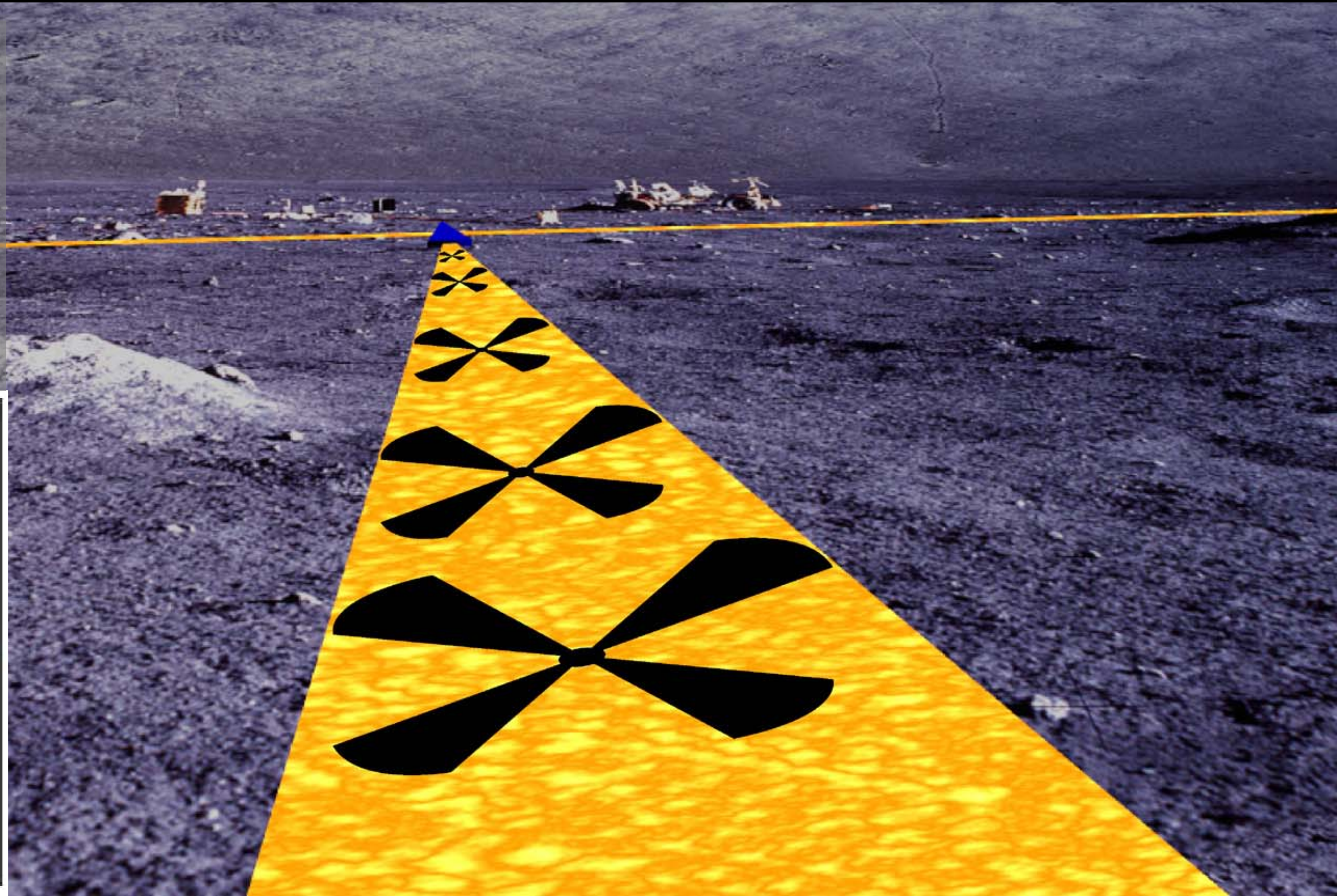
$$\Delta T_{min} = T_{sys}/(\Delta\nu \cdot t)^{1/2}$$

where T_{sys} = sky temperature ~17,000 K at 30 MHz

ROLSS: Radio Observatory for Lunar Science Sortie

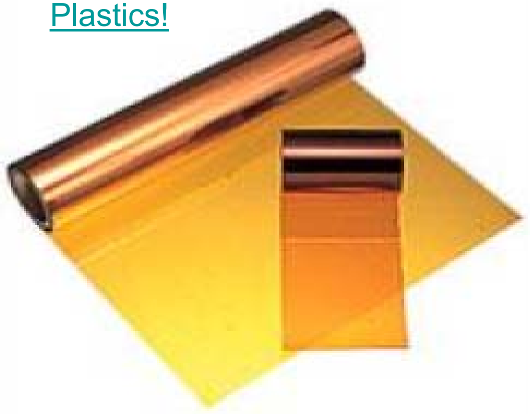


A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km). Operating at 1-10 MHz (30-300 m). Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.

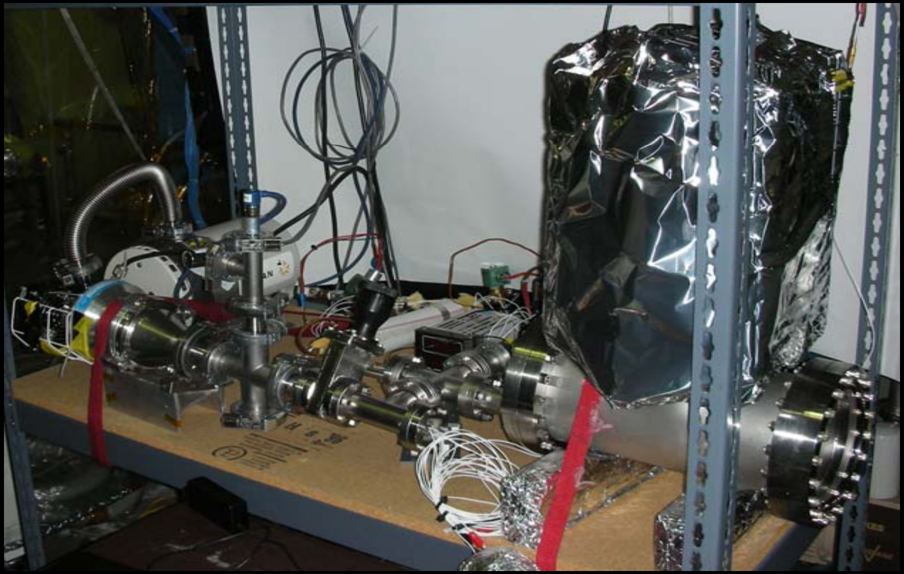


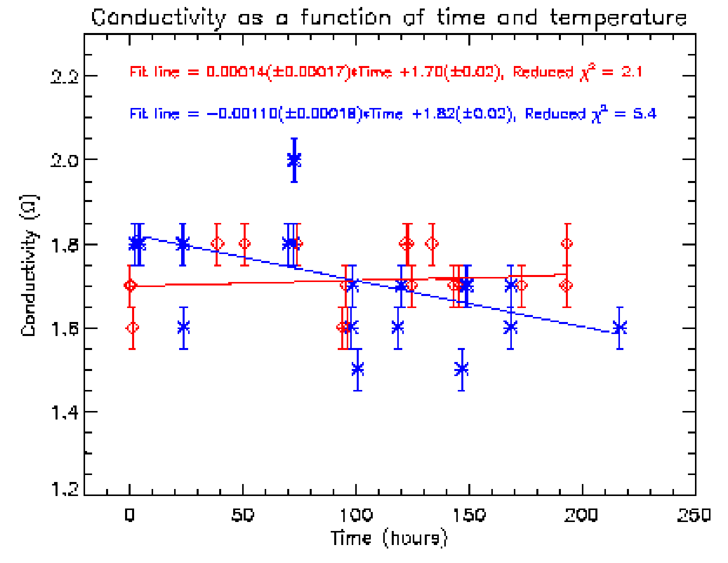
- Arms are thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).

Plastics!



Laboratory Testing of Polyimide Film as Low Frequency Antenna Backbone



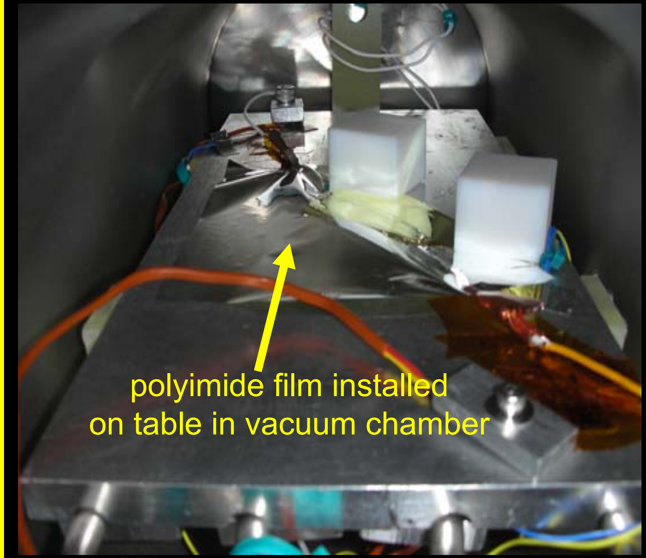


Experimental Set-up

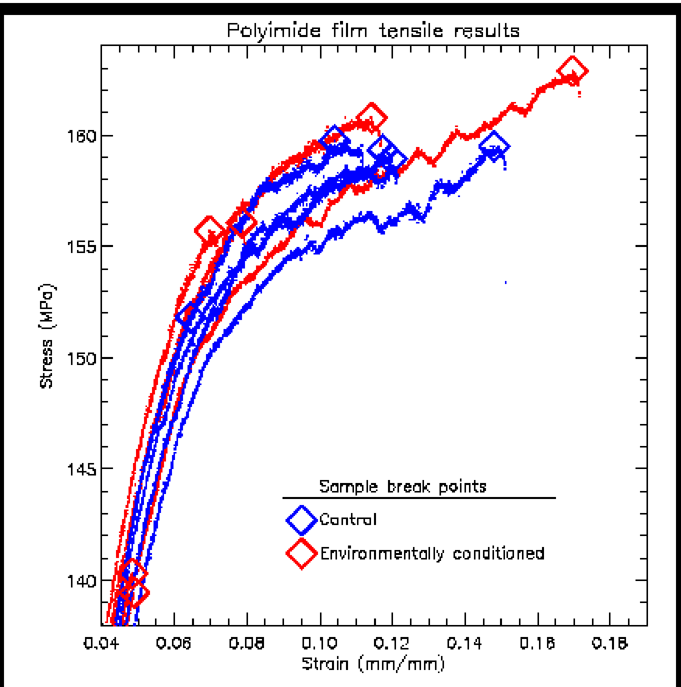
- 12 24-hr duty cycles with T = -150 C to 100 C.
- Exposed to UV with deuterium lamp during "day cycle".

Results

- No significant change in material or electrical characteristics during thermal cycling.

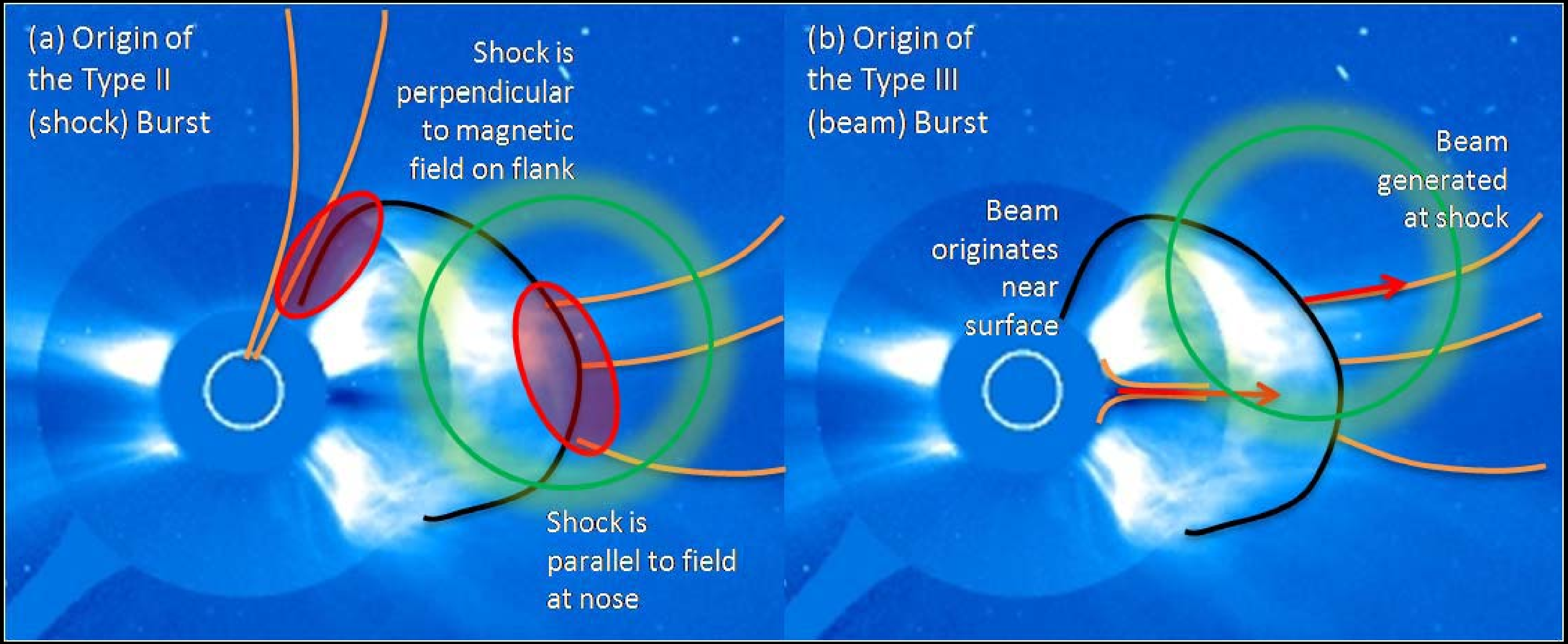


polyimide film installed on table in vacuum chamber



In collaboration with Ted Schultz and Bobby Kane, CU CASA

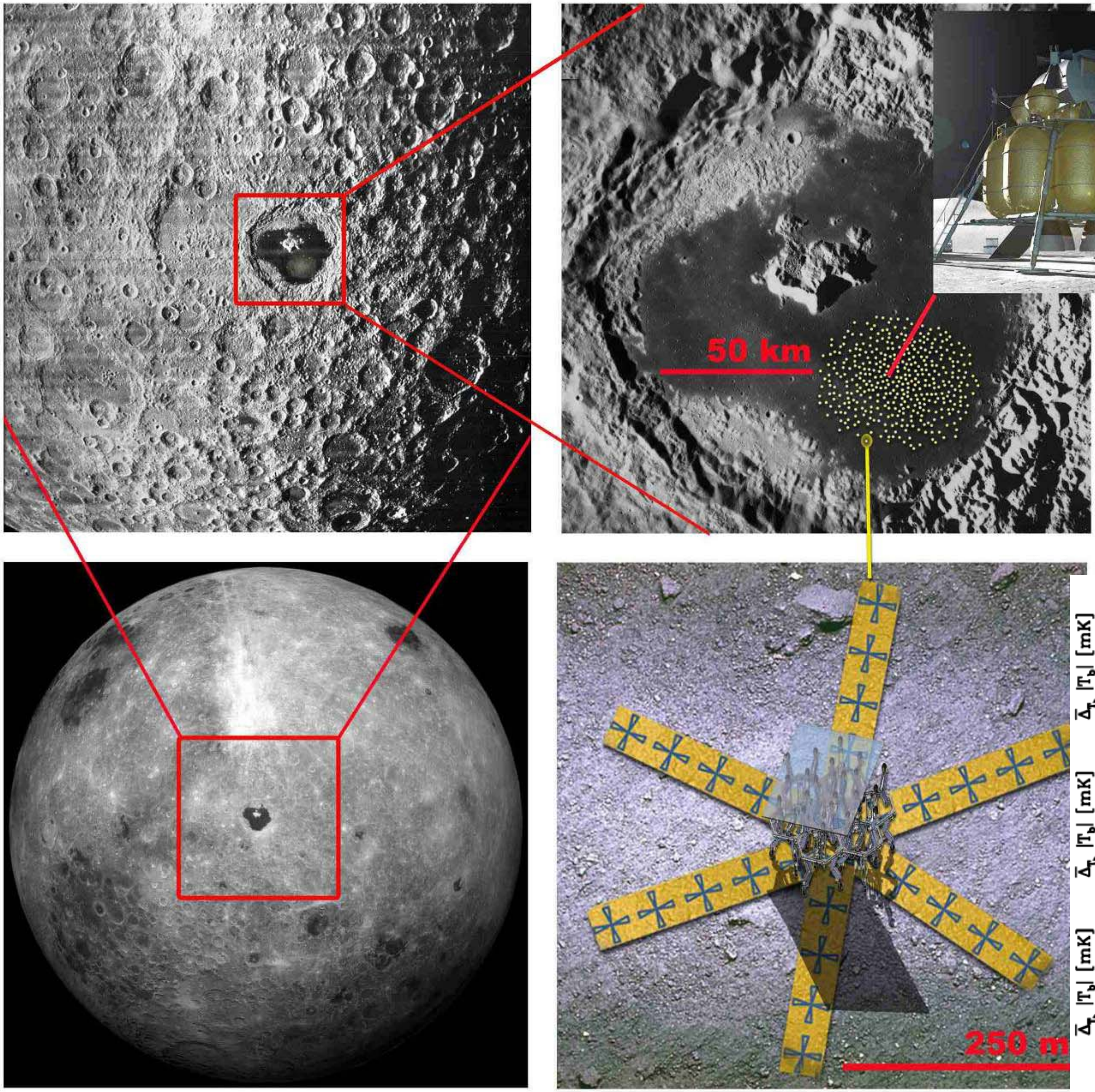
Solar Science with ROLSS



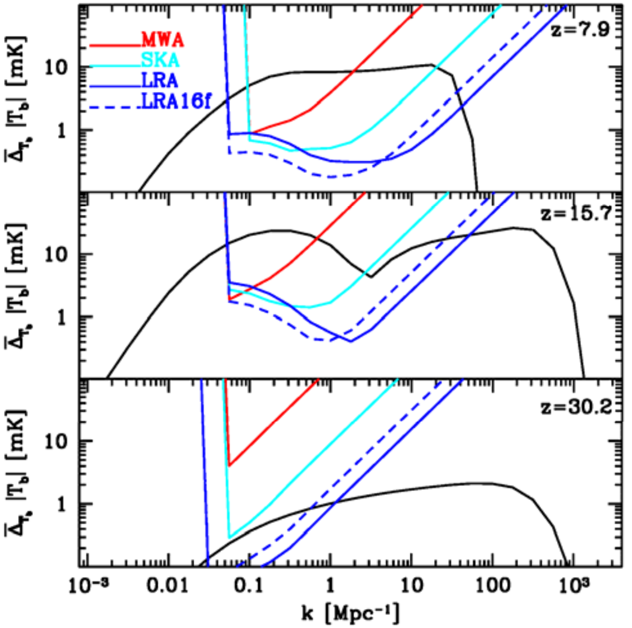
Type II Burst source location **Complex Type III source location**

- ROLSS will produce the first high angular resolution (<1° at 10 MHz), high time resolution images of solar radio emissions (outer corona).
- ROLSS will study how high energy particles are generated on the Sun. This radiation is a danger to future astronauts.

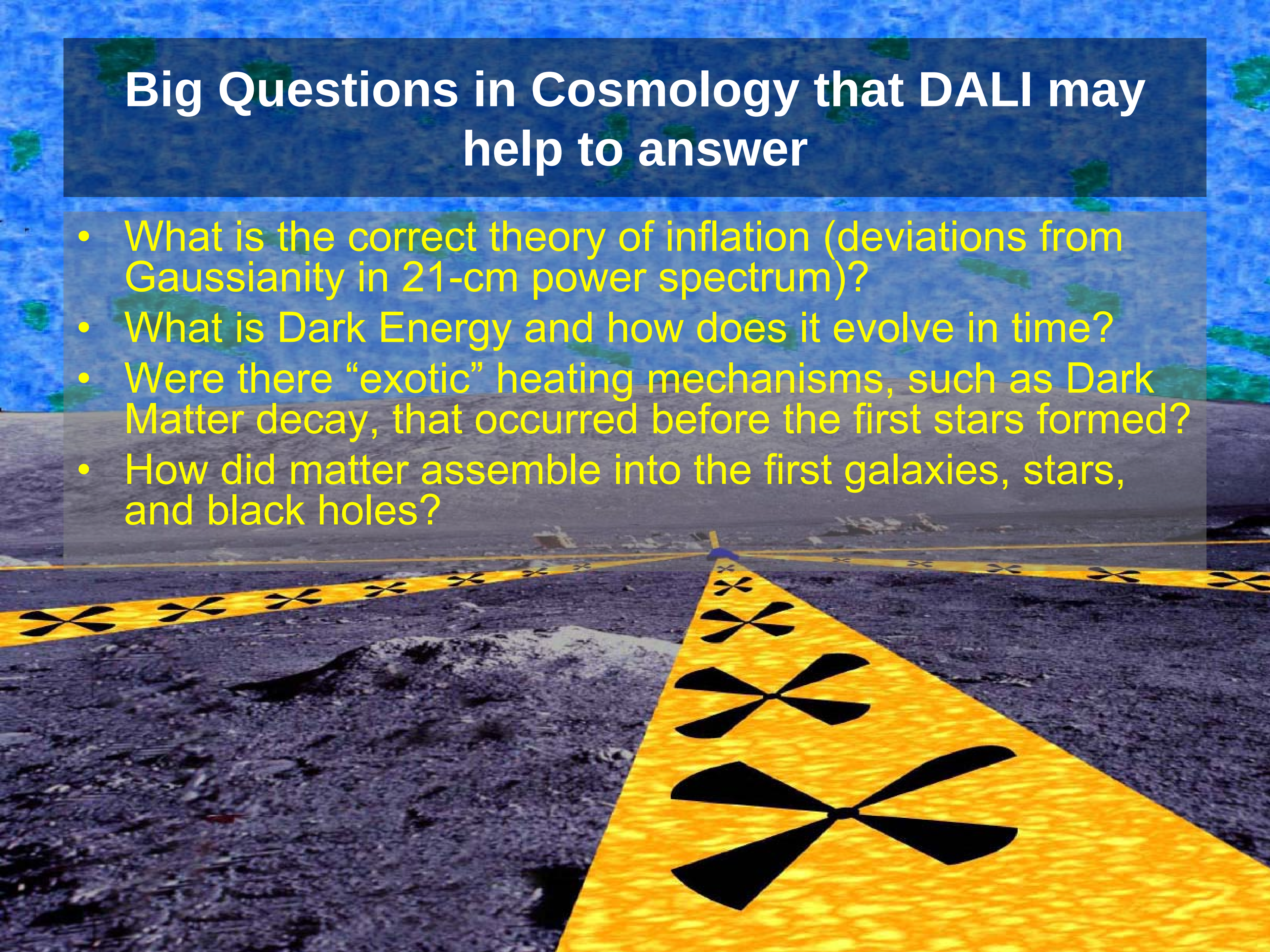
Dark Ages Lunar Interferometer (DALI)



DALI concept. (*Left, upper right*): Possible location in the Tsiolkovsky crater. (*Upper right insert*): Artist's concept of lander; DALI would have pallets of rovers instead of an astronaut habitat module. (*Lower right*): Individual station contains ~100 electrically-short dipoles. ~1000 stations are planned.



Big Questions in Cosmology that DALI may help to answer



- What is the correct theory of inflation (deviations from Gaussianity in 21-cm power spectrum)?
- What is Dark Energy and how does it evolve in time?
- Were there “exotic” heating mechanisms, such as Dark Matter decay, that occurred before the first stars formed?
- How did matter assemble into the first galaxies, stars, and black holes?

Constraints on Gravitational Physics: Lunar Laser Ranging


Apollo 14 retroreflector at Fra Mauro

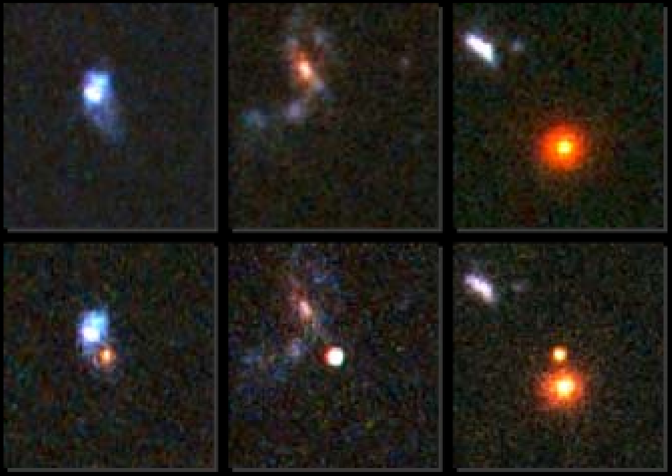

APOLLO = Apache Point Observatory Lunar Laser-ranging Operation

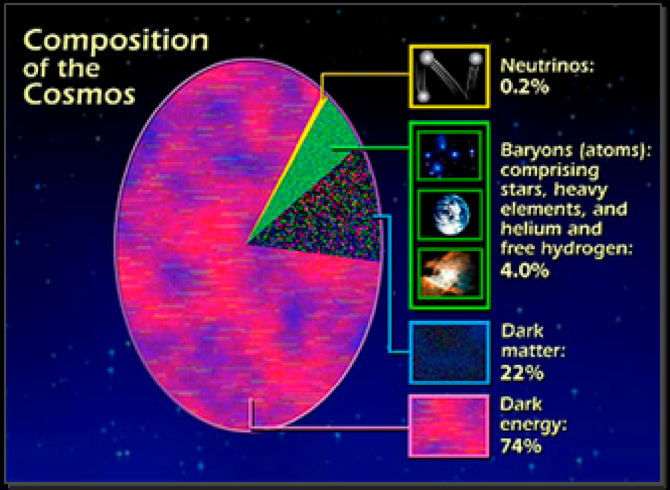
Current Capabilities

- Accuracy ≈ 1 mm.
- Strong Equivalence principle $\eta < 4.5 \times 10^{-4}$.
- $\dot{G}/G < 10^{-12}$ per year.
- Deviation from inverse-square law is $< 10^{-10}$ times strength of gravity at 10^{8} m scales.

Lead Scientists: T. Murphy, D. Currie, S. Merkowitz

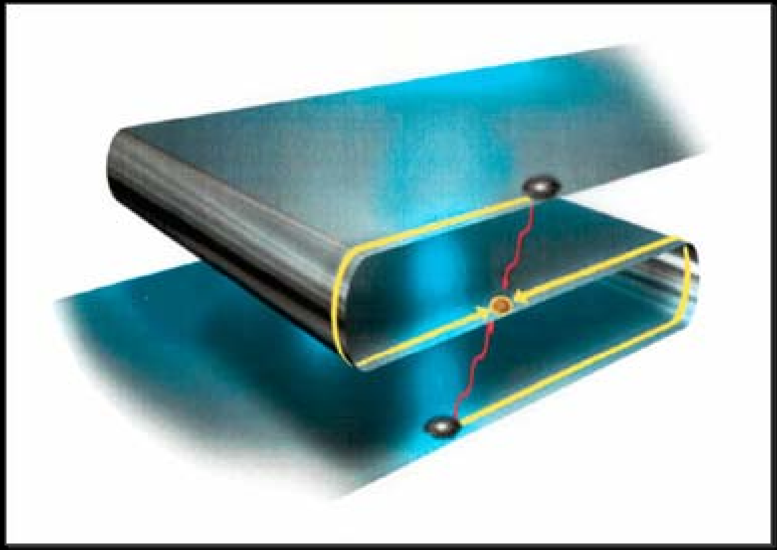
Dark Energy or Alternative Gravity





- Currently envisioned to be addressed by wide-field observations from free space (JDEM).

$$H^2 - \frac{H}{r_c} = \frac{8\pi}{3} G_N \left(\rho + \rho_{DE}\right)$$

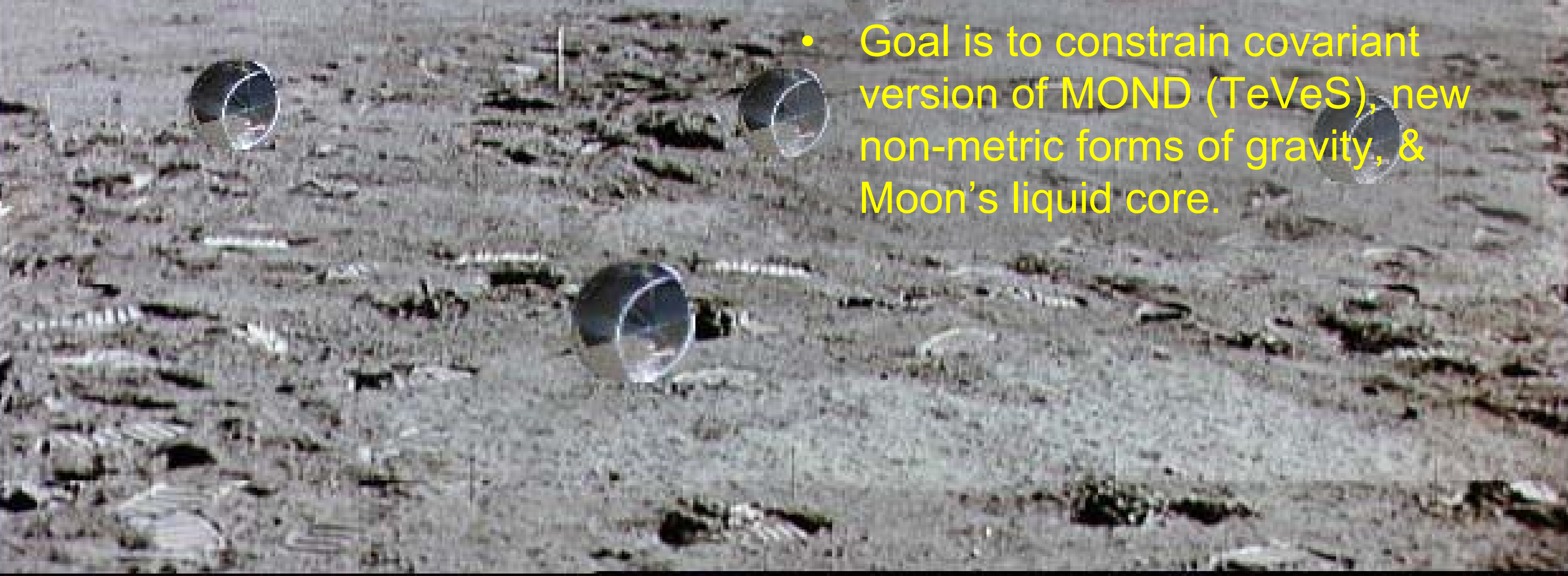


- Can be tested by experiments on the lunar surface; laboratory and accelerator experiments.

Next-Generation Laser Retroreflector Array for the Moon

Capabilities

- Reduce temporal spread by a sparse arrangement of corner cubes.
- Accuracy goal = 10 μm which improves limits on gravity by factor of 1000.
- Goal is to constrain covariant version of MOND (TeVeS), new non-metric forms of gravity, & Moon’s liquid core.

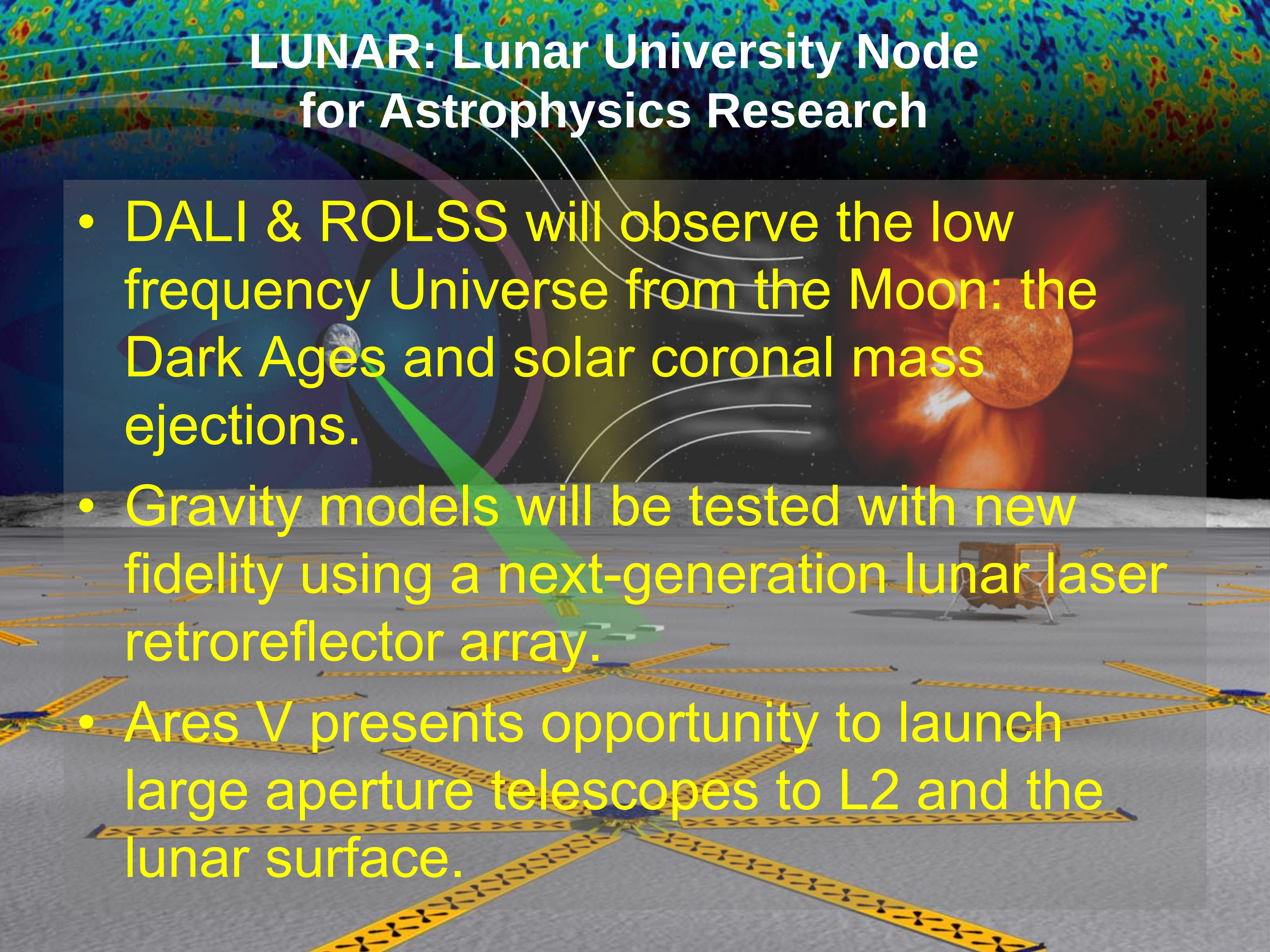


Ares V enables a fully deployed 8-m or folded, segmented 15 - 20m telescope to be deployed in a single launch.

Conception of 8-m monolithic optical space telescope in Ares V

Without Ares V, multiple launches, complex folded optics, and/or on-orbit assembly would be the only alternatives for deploying space telescopes larger than ~7-m.

LUNAR: Lunar University Node for Astrophysics Research



- DALI & ROLSS will observe the low frequency Universe from the Moon: the Dark Ages and solar coronal mass ejections.
- Gravity models will be tested with new fidelity using a next-generation lunar laser retroreflector array.
- Ares V presents opportunity to launch large aperture telescopes to L2 and the lunar surface.