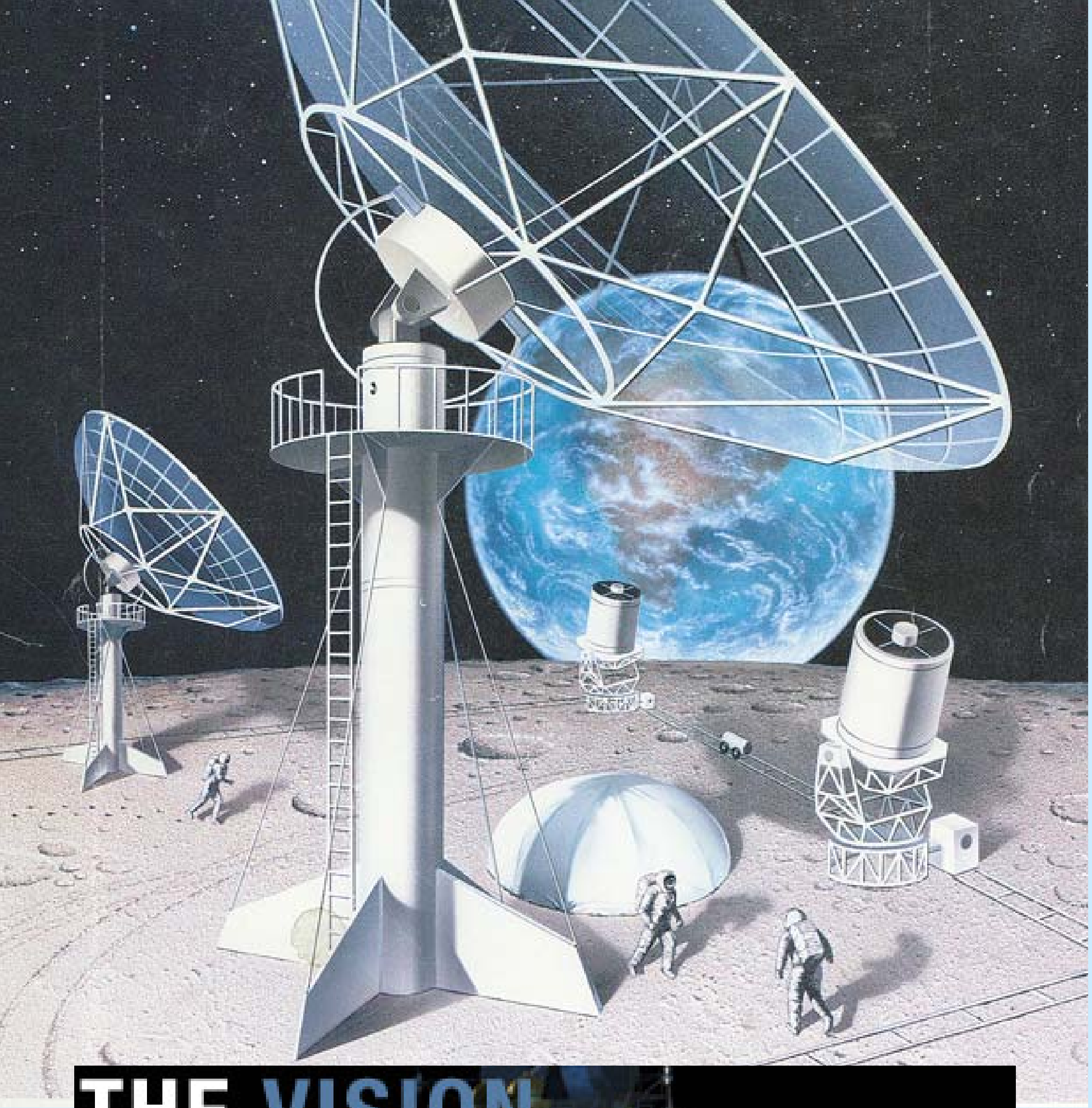



# Probing Into The "Dark Ages" with a Low Frequency Interferometer on the Moon

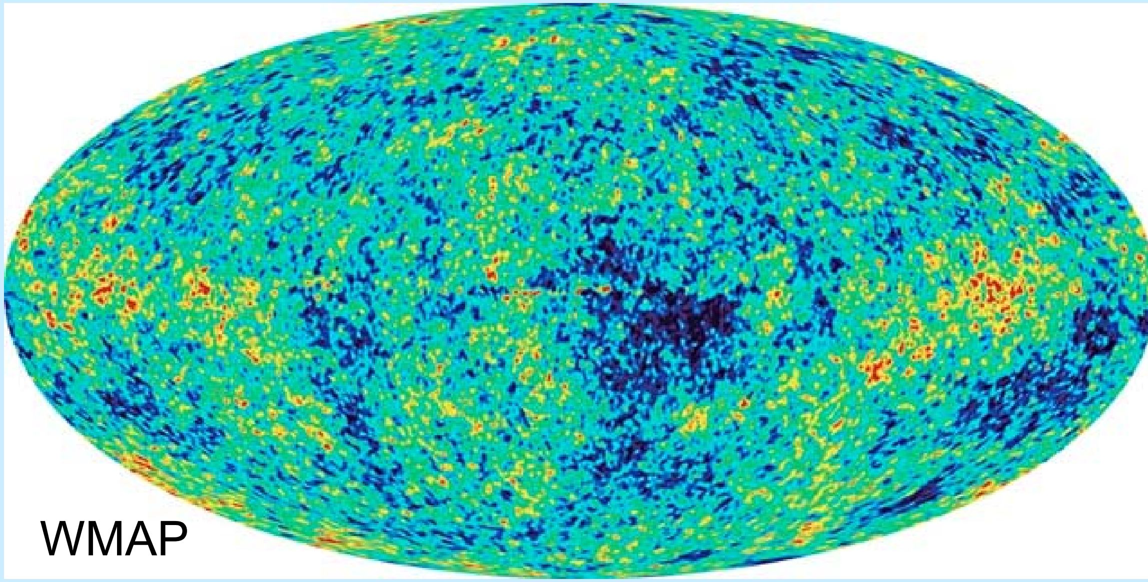
**Jack Burns**
Center for Astrophysics and Space Science
University of Colorado, Boulder

(with contributions from A. Loeb, J. Hewitt, C. Carilli, J. Lazio)

JILA Seminar
April 13, 2007

**From the CMB**

**400,00 yrs after Big Bang**




# The Universe In Transition

**Recombination (400,000 yrs)**

**The Dark Ages**

**Reionization & 1$^{st}$ stars (10$^{8}$ yrs)**

**To**

**Today**

**Clusters Of Galaxies**

HST

*TIME Magazine cover story, 9/2006*

# Light From a Dark Age

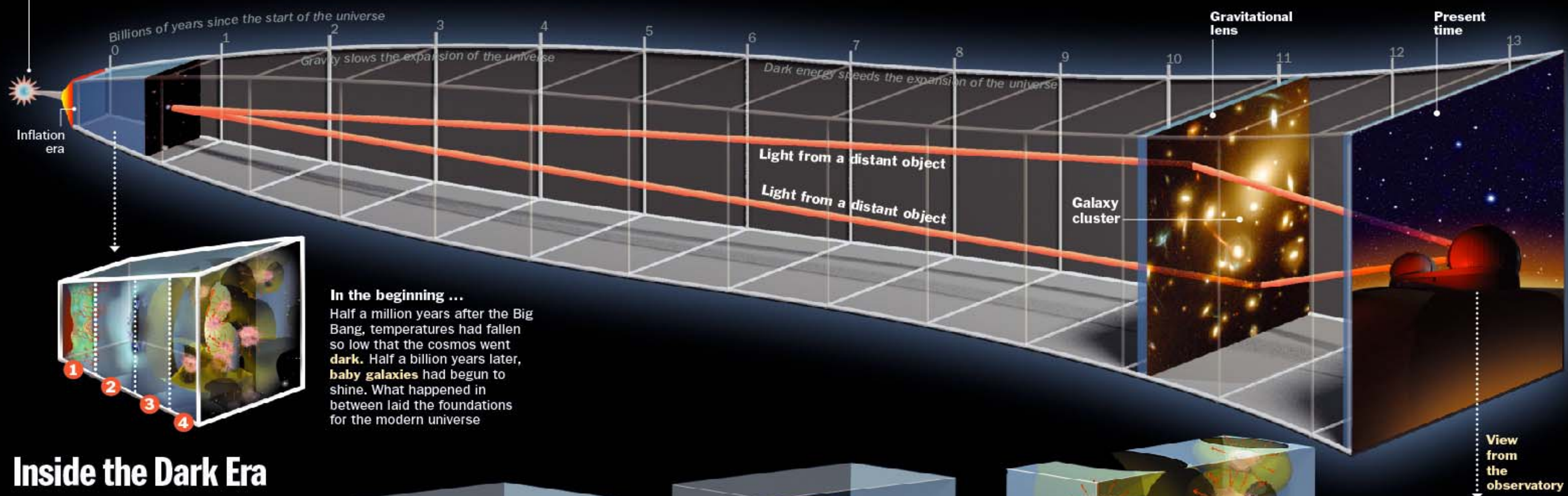
## How the universe grew from dark soup to twinkling galaxies

### Looking for the beginning of time …

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

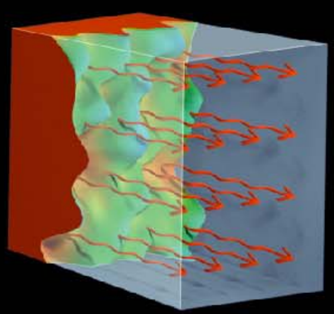
### … 13.4 billion years later

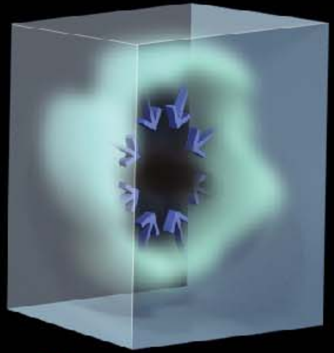
Albert Einstein suggested that **gravity** from a massive forergound object could distort and magnify background objects. By looking through a **cluster of galaxies**, astronomers have now found the magnified images of much more distant galaxies

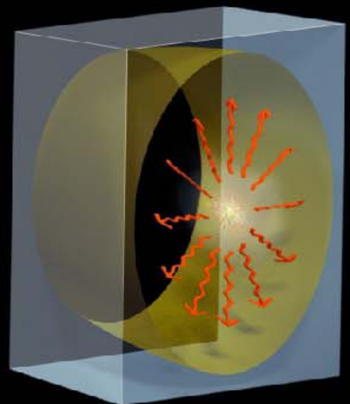


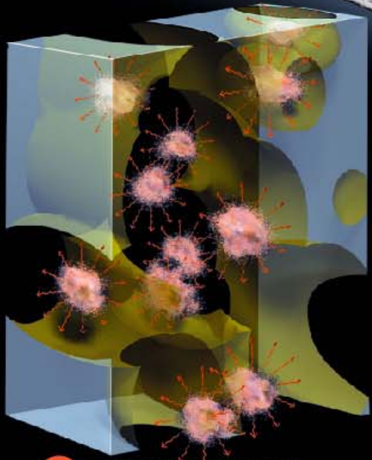

**In the beginning …**
Half a million years after the Big Bang, temperatures had fallen so low that the cosmos went **dark.** Half a billion years later, **baby galaxies** had begun to shine. What happened in between laid the foundations for the modern universe

## Inside the Dark Era







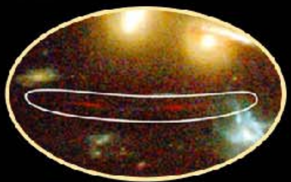


**1 THE DARK AGES BEGIN**
When the cosmos is about **400,000 years** old, it has cooled to about the temperature of the surface of the Sun, allowing subatomic particles to combine for the first time into **atoms.** The last burst of light from the Big Bang shines forth at this time; it is still detectable 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**

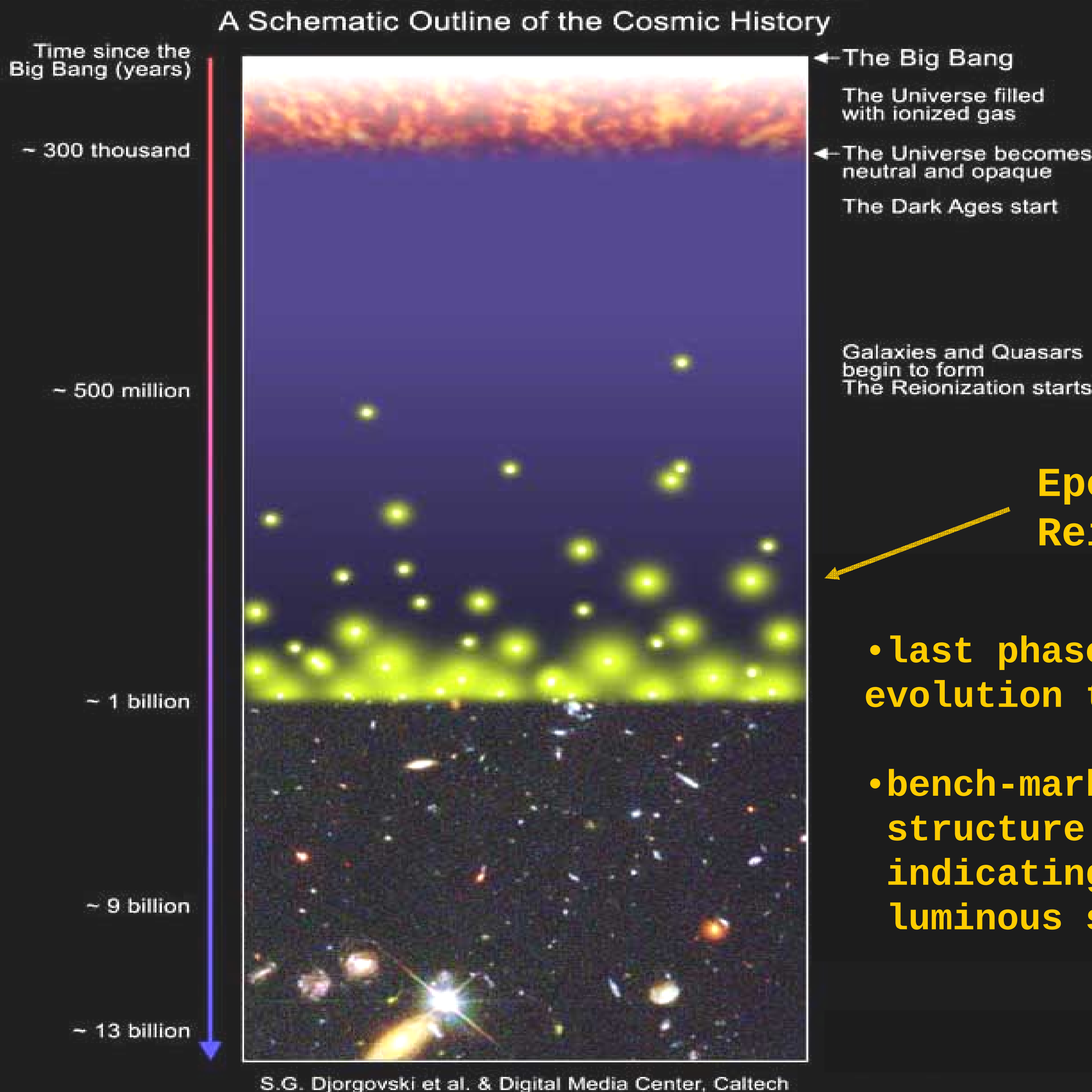
**4 END OF THE DARK AGES**
The death of the megastars triggered the formation of normal stars, creating the first normal-looking **dwarf galaxies.** Their radiation in turn burned through the remaining shrouds of hydrogen, bringing the dark ages to a close.



### 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**

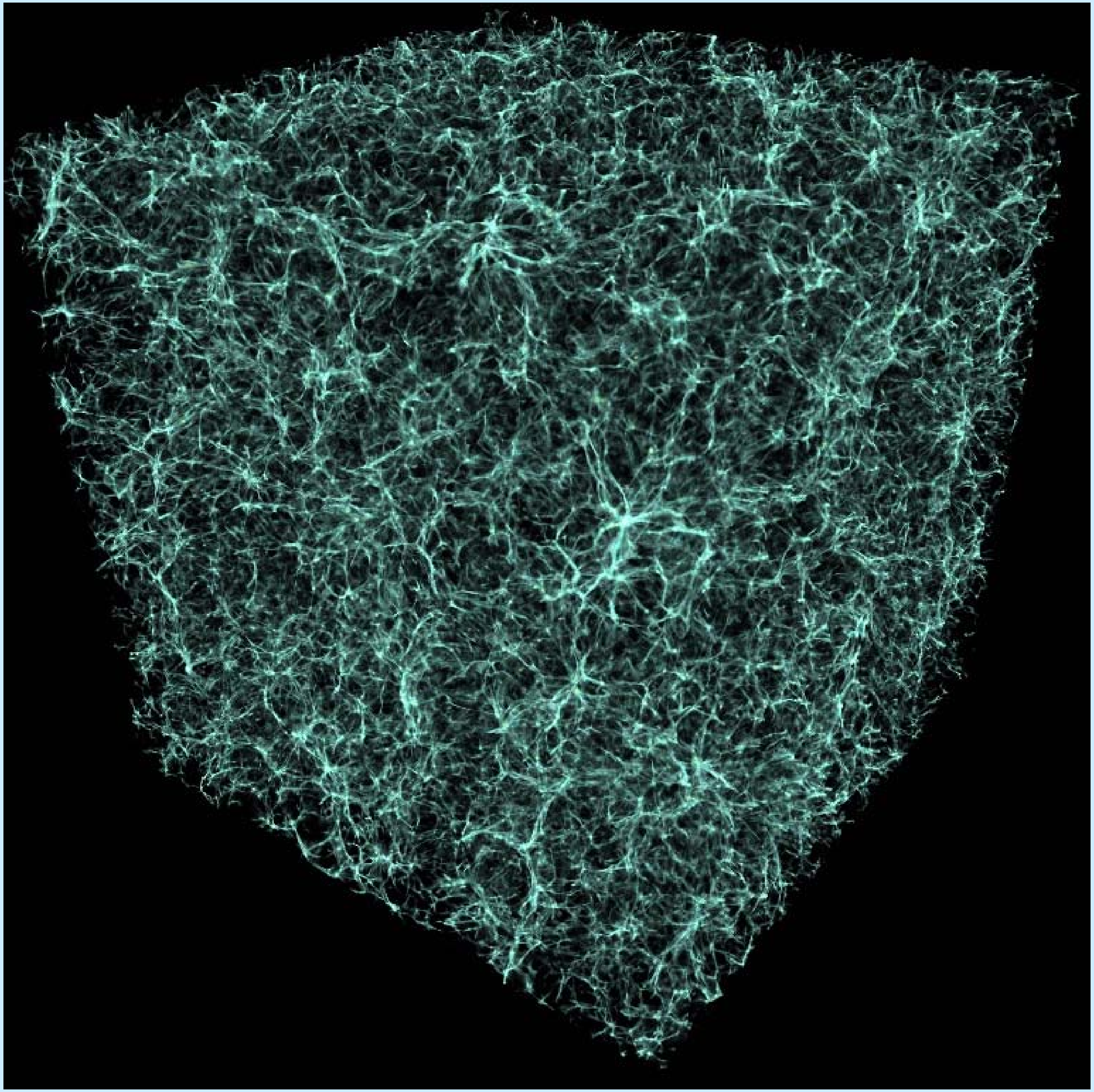
TIME Graphic by Joe Lertola
Sources: TKTKTK




$z \approx 20$

**Epoch of Reionization**

- **last phase of cosmic evolution to be explored**
- **bench-mark in cosmic structure formation indicating the first luminous structures**



# Emergence of Baryonic Structure In The Universe

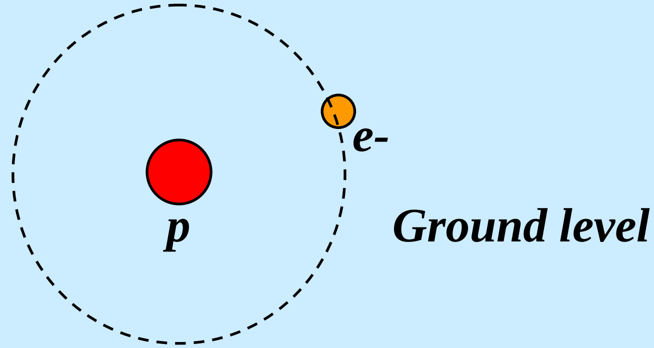
LCDM Hydo +
N-body "Santa Fe"
Light Cone
Simulation using Enzo


*E. Hallman and J. Burns*
University of Colorado

*B. O'Shea*
Los Alamos National Lab

*M. Norman*
U. California – San Diego

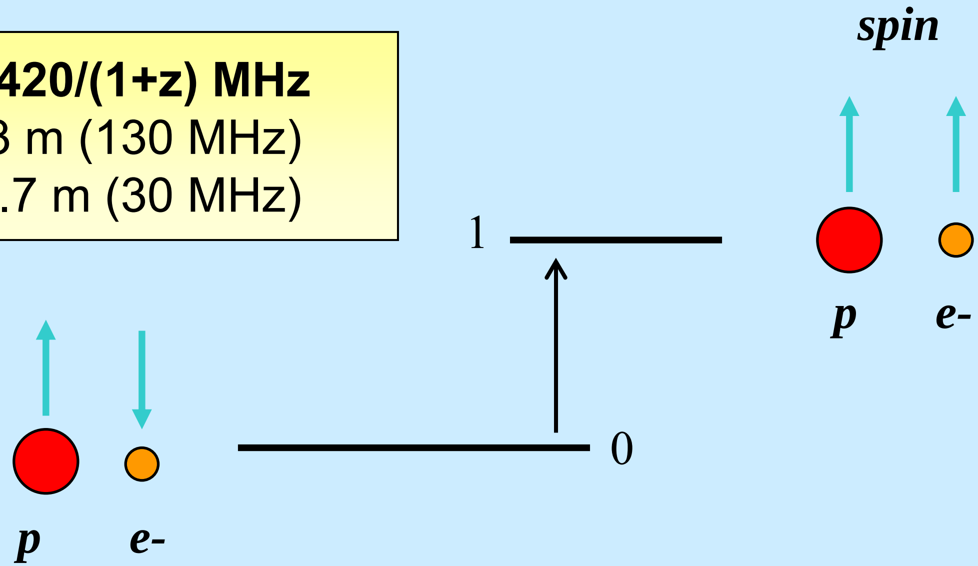
# Hydrogen




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

***Couple*** $T_s$ ***to*** $T_k$ ***Couples*** $T_s$ ***to*** $\mathbf{T_{CMB}}$

**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)

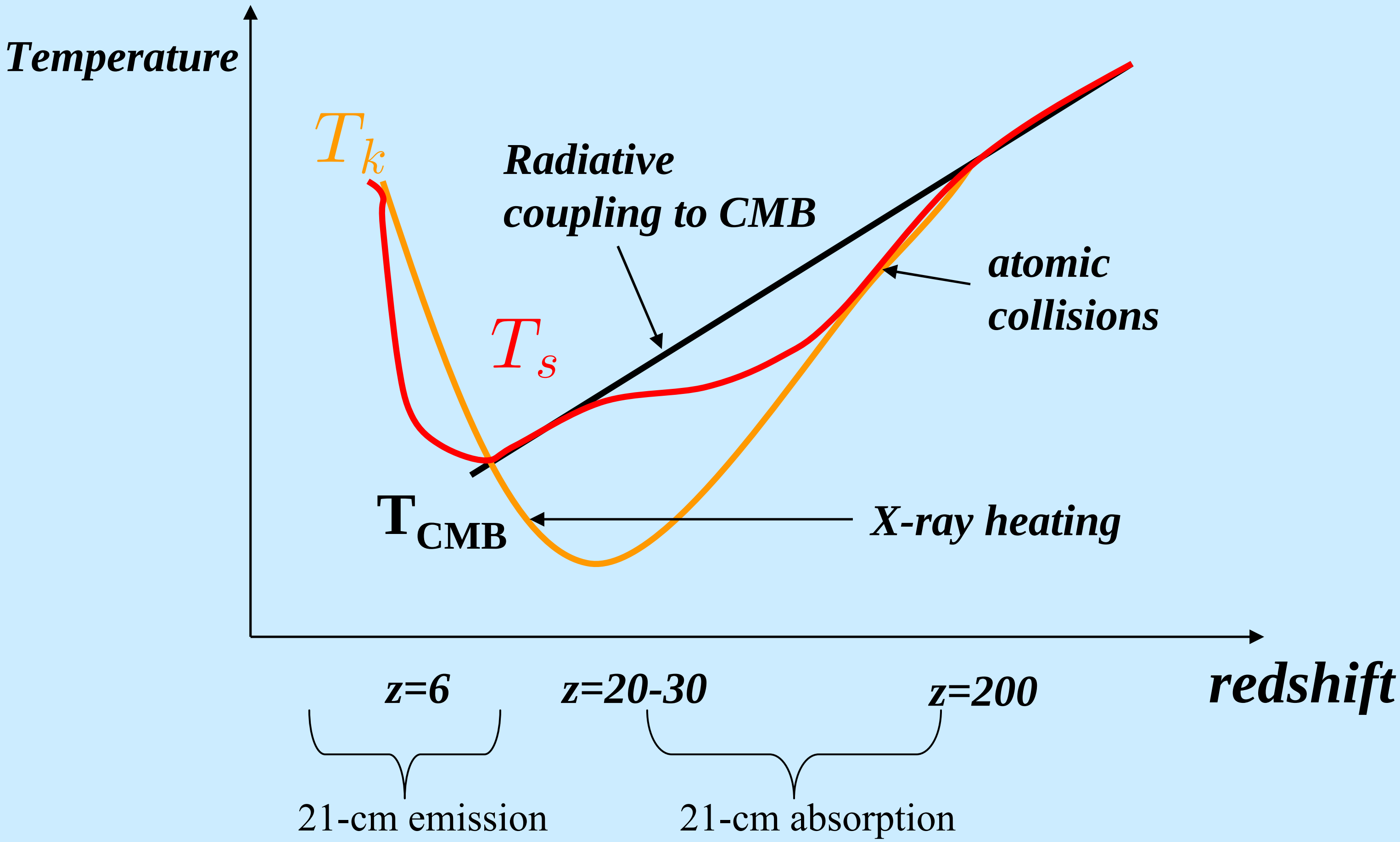



$\mathbf{n_1/n_0 = g_1/g_0 \exp(-T_*/T_s)}$ where $g_1/g_0=3$, $T_*=0.068$ K

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

# Thermal History

(adapted from Loeb, 2006, astro-ph/063360)




## Sources of 21cm fluctuations

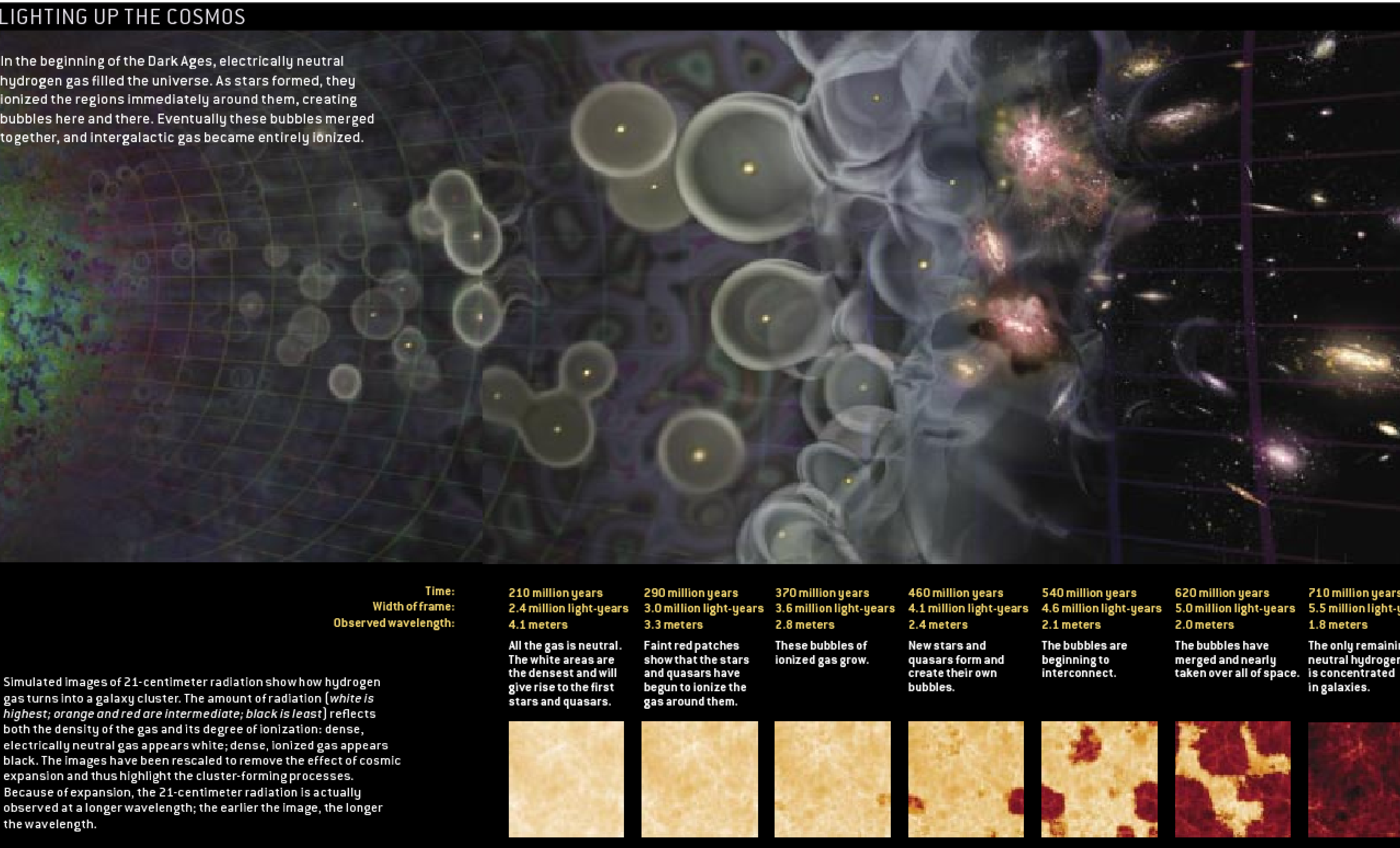
*Density inhomogeneties (Loeb & Zaldarriaga 04) and peculiar velocities (Barkana & Loeb 04)*

*Ionized bubbles (Madau,Meiksin &Rees 1997;Furlanetto et al. 2004; Gnedin & Shaver 2003)*

*Emision from mini-halos (Iliev, Shapiro, et al. 2002)*

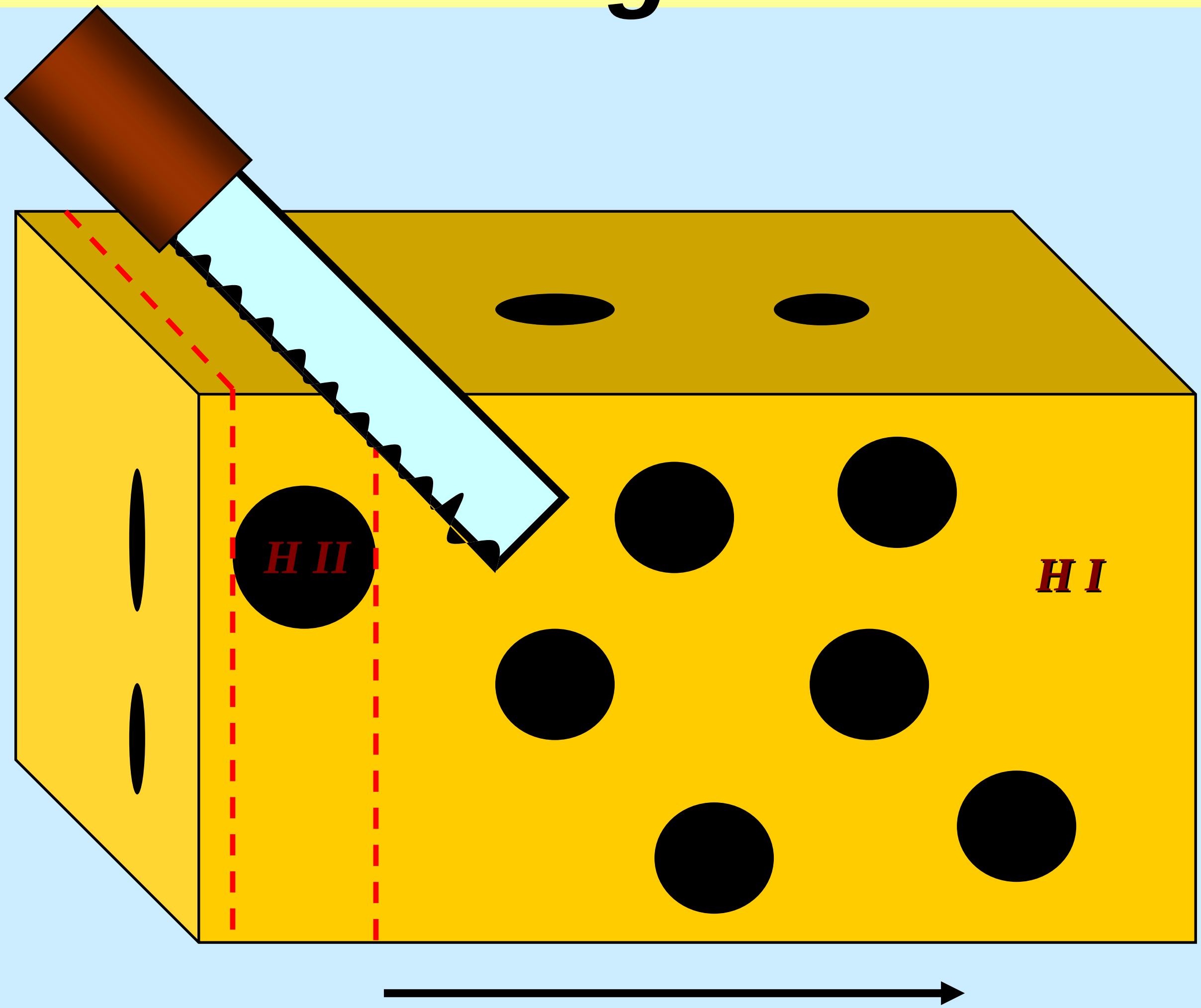
*Fluctuations in Lya flux, and gas temperature (Barkana & Loeb 2004)*

**A. Loeb, *Scientific American*, November 2006**




Sharpness of bubbles will differentiate between massive stars vs. black holes as source of reionization.

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




***Observed wavelength ⇔ distance***

**21cm (1+z)**

(Loeb, 2006, astro-ph/063360)

# Experiments on the Ground

***MWA (Mileura Wide-Field Array) in Australia***

*MIT/ATNF/CfA* (80-300 MHz)

*** LWA (Long Wavelength Array)***

*U. New Mexico/NRL/LANL/U. Texas*
(20-80 MHz)

***LOFAR (Low-frequency Array)***

*Netherlands* (30-80 MHz)

***21CMA (formerly known as** PAST)*

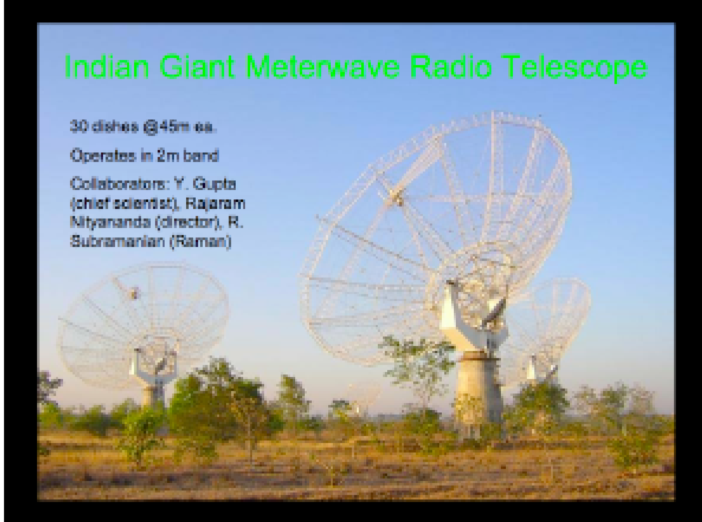
*China*

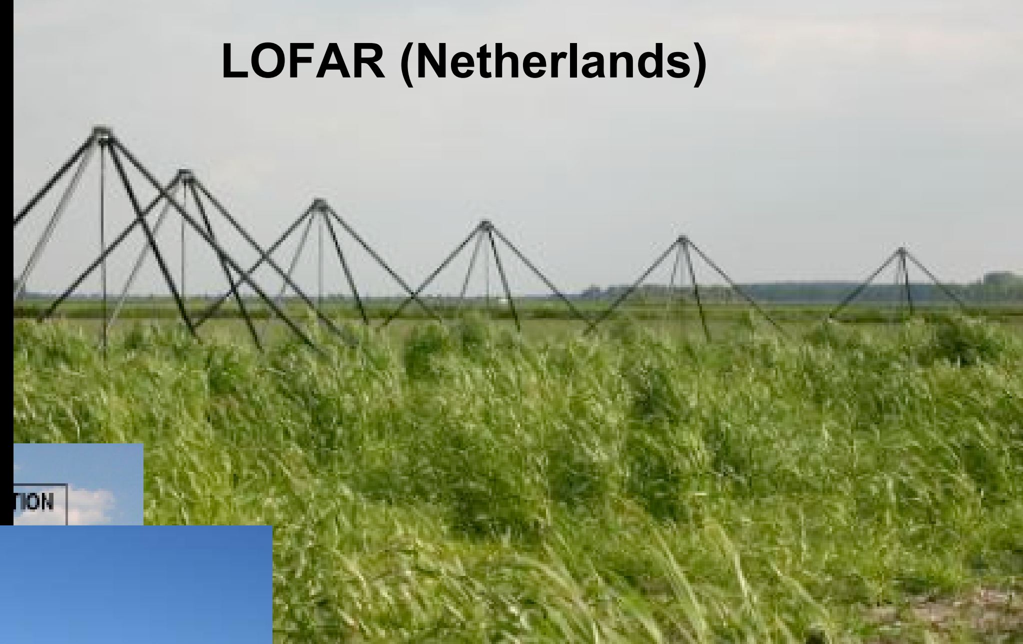
***GMRT (Giant Meterwave Radio Telescope)***

*India/CITA/Pittsburg*

***SKA (Square Kilometer Array)***

*International*


Indian Giant Meterwave Radio Telescope
30 dishes @45m ea.
Operates in 2m band
Collaborators: Y. Gupta (chief scientist), Rajaram Nityananda (director), R. Subramanian (Raman)

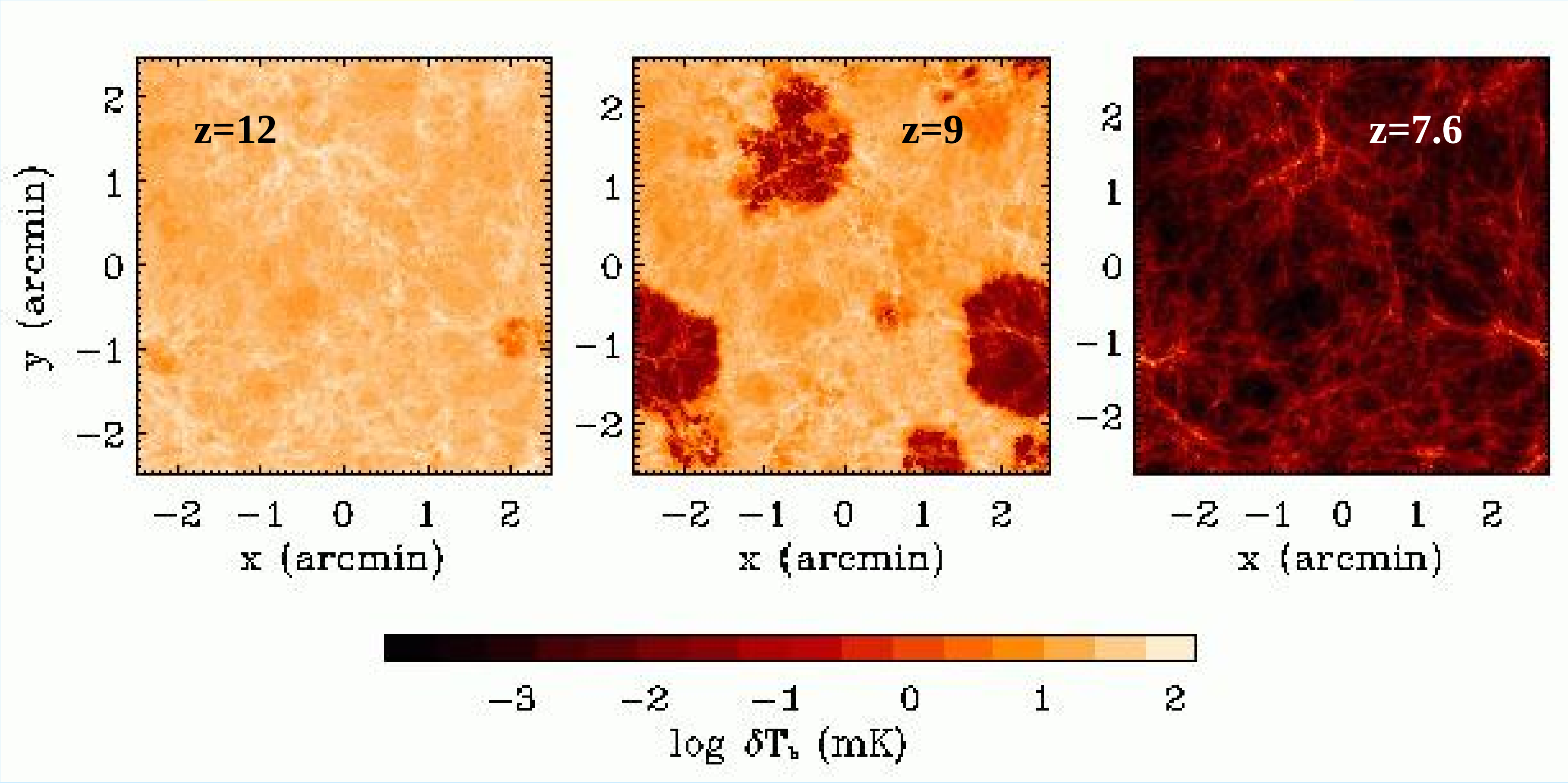

LOFAR (Netherlands)


Long Wavelength Array
(VLA site in NM)


MWA (Western Australia)

# HI 21cm Tomography of IGM

Zaldarriaga, 2003




- $\Delta T_B(2')$ = 10's mK => DNR > $10^5$
- LOFAR rms (1000hr) = 80mK
- SKA rms(100hr) = 4mK

courtesy C. Carilli

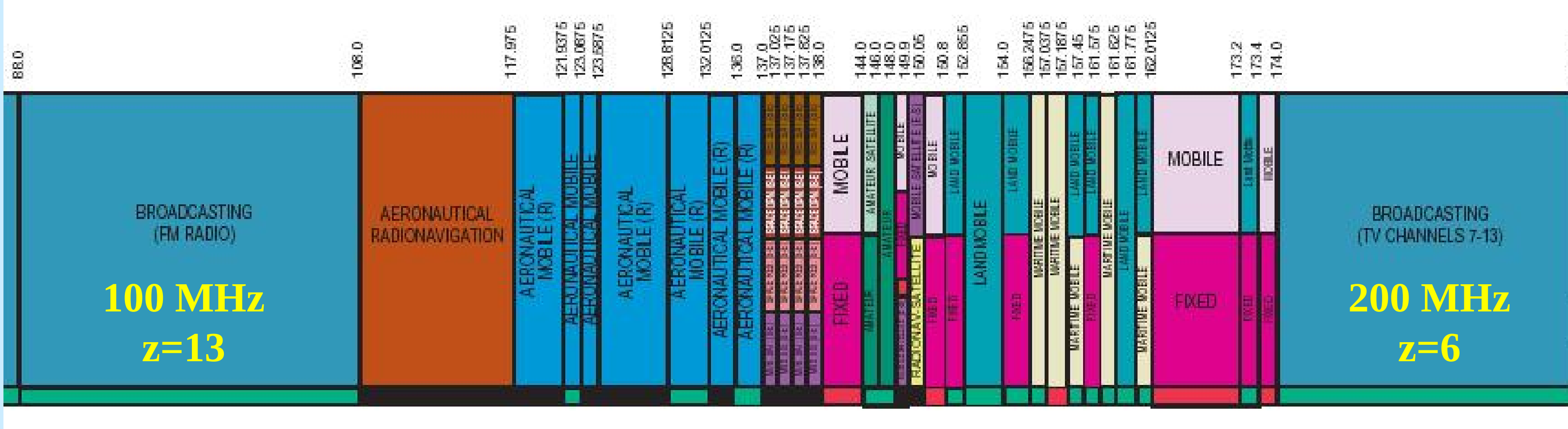
# Primary Challenge for Earth Arrays: Foregrounds

- Terrestrial: radio broadcasting
- Ionospheric distortions
- Galactic synchrotron emission
- Extragalactic: radio sources
  (*Di-Matteo et al. 2004*)

***Although the sky brightness (>10K) is much larger than the 21cm signal (<10mK), the foregrounds have a smooth frequency dependence while the signal fluctuates rapidly across small shifts in frequency (=redshift). Preliminary estimates indicate that the 21cm signal is detectable with the forthcoming generation of low-frequency arrays (Zaldarriaga et al. astro-ph/0311514; Morales & Hewitt astro-ph/0312437)***

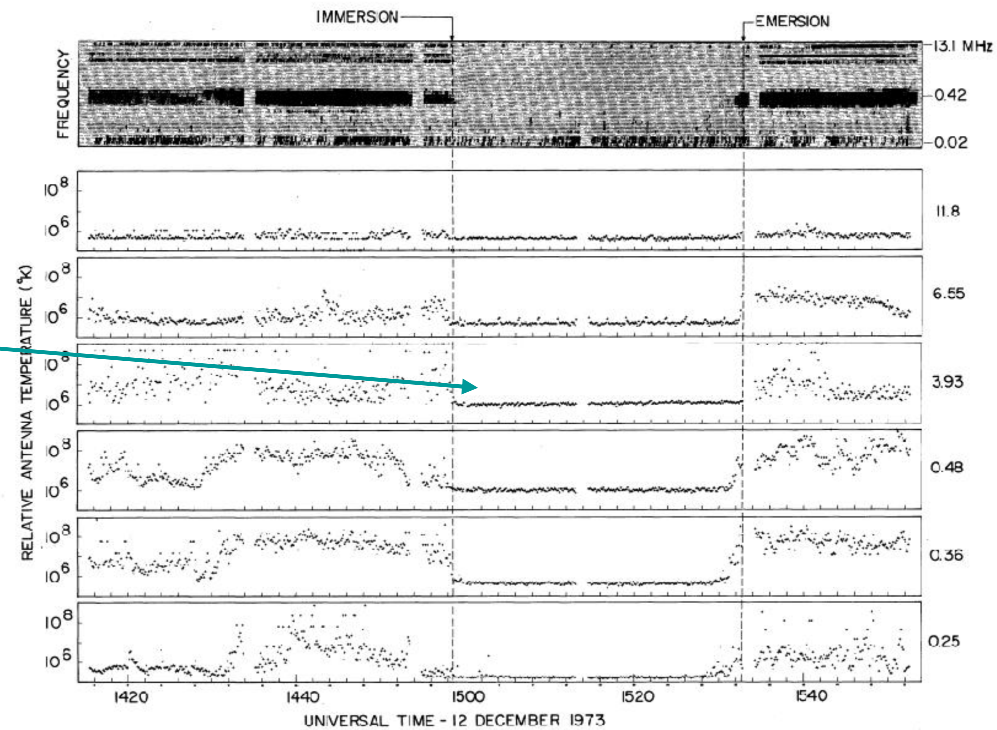
# Lunar Advantage I: Interference

(courtesy C. Carilli, 2006)





RAE-2 1973

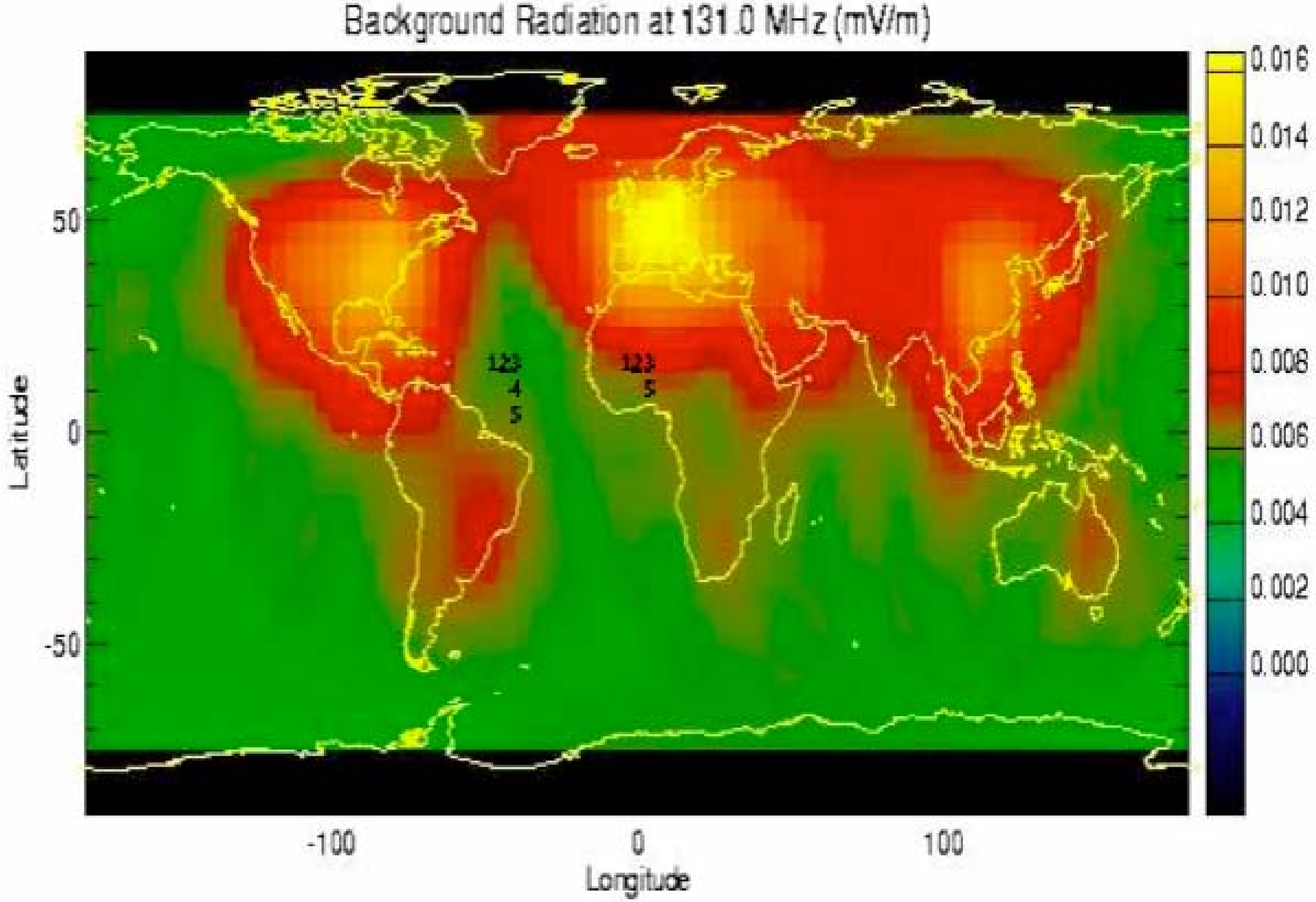



5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time ations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 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 the receiver the burst receiver are tuned to the same frequency

370

J. K. Alexander et al.

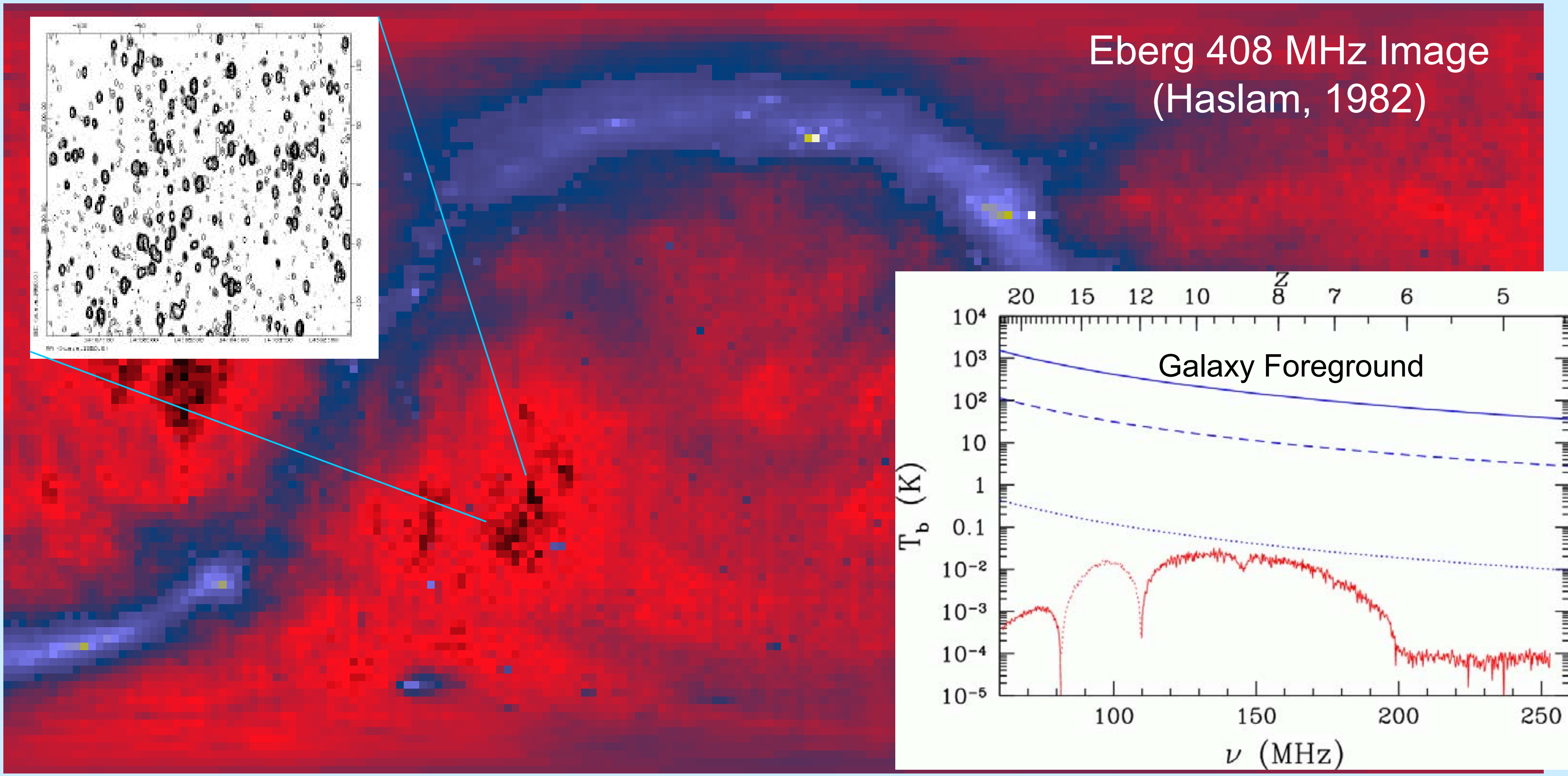
# Radio Frequency Interference




FORTES satellite

# Remaining challenge: Low Frequency Background

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




Solution: fitting in the spectral domain

courtesy C. Carilli

# *Very low frequency (<30MHz): pre-reionization HI signal*

# → Lunar imperative: e.g., Baryon Oscillations (Barkana & Loeb)

<u>Very difficult to detect</u>

- Signal: 10 arcmin, 10mK

=> $S_{30MHz}$ = 0.02 mJy

- SKA sens in 1000 hrs:

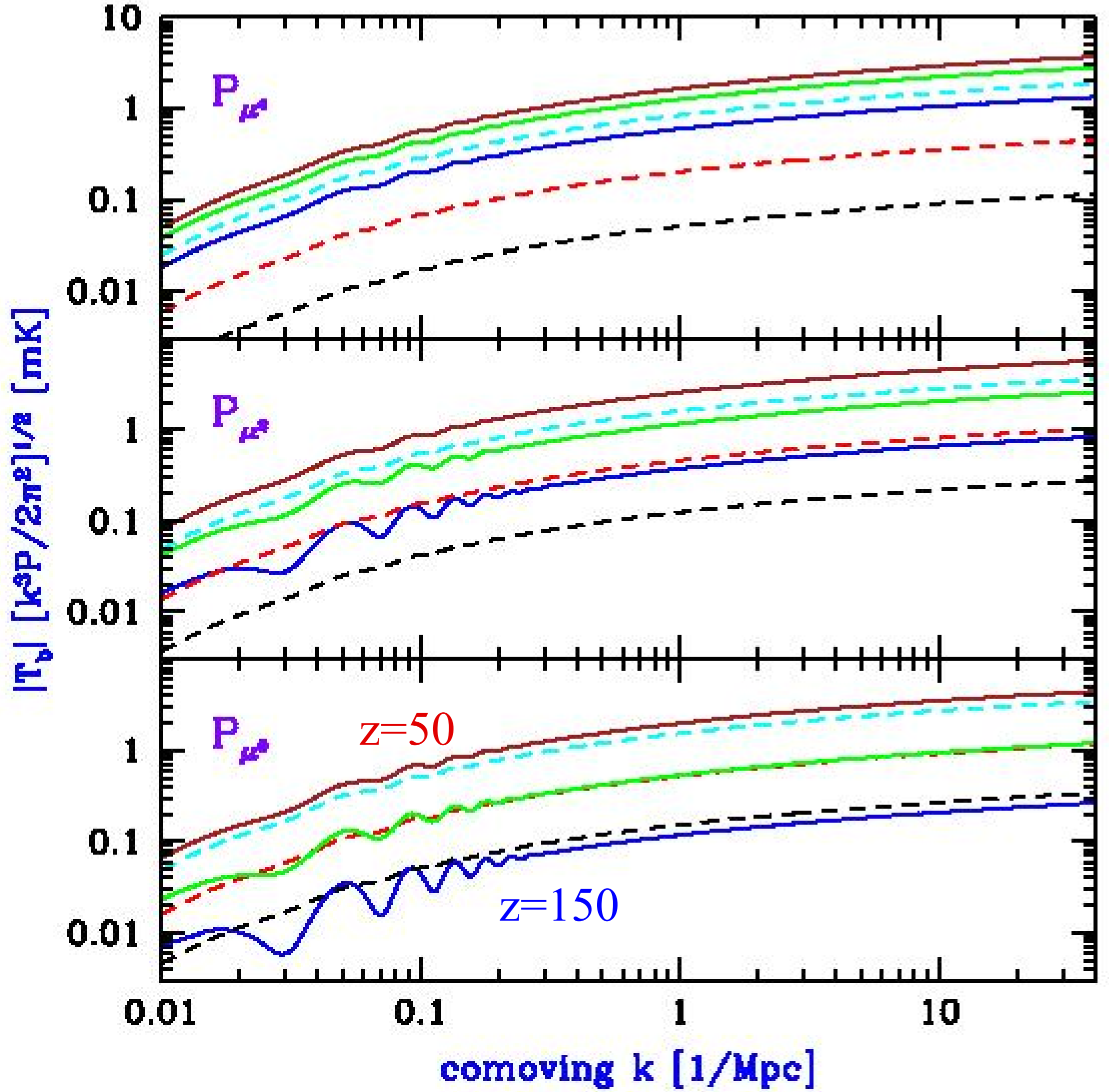
T= 100(ν/200 MHz)$^{-2.7}$ K

= 20,000K at 30MHz =>

rms = 0.2 mJy

**Need > 10 SKAs**

**Need DNR > $10^6$**

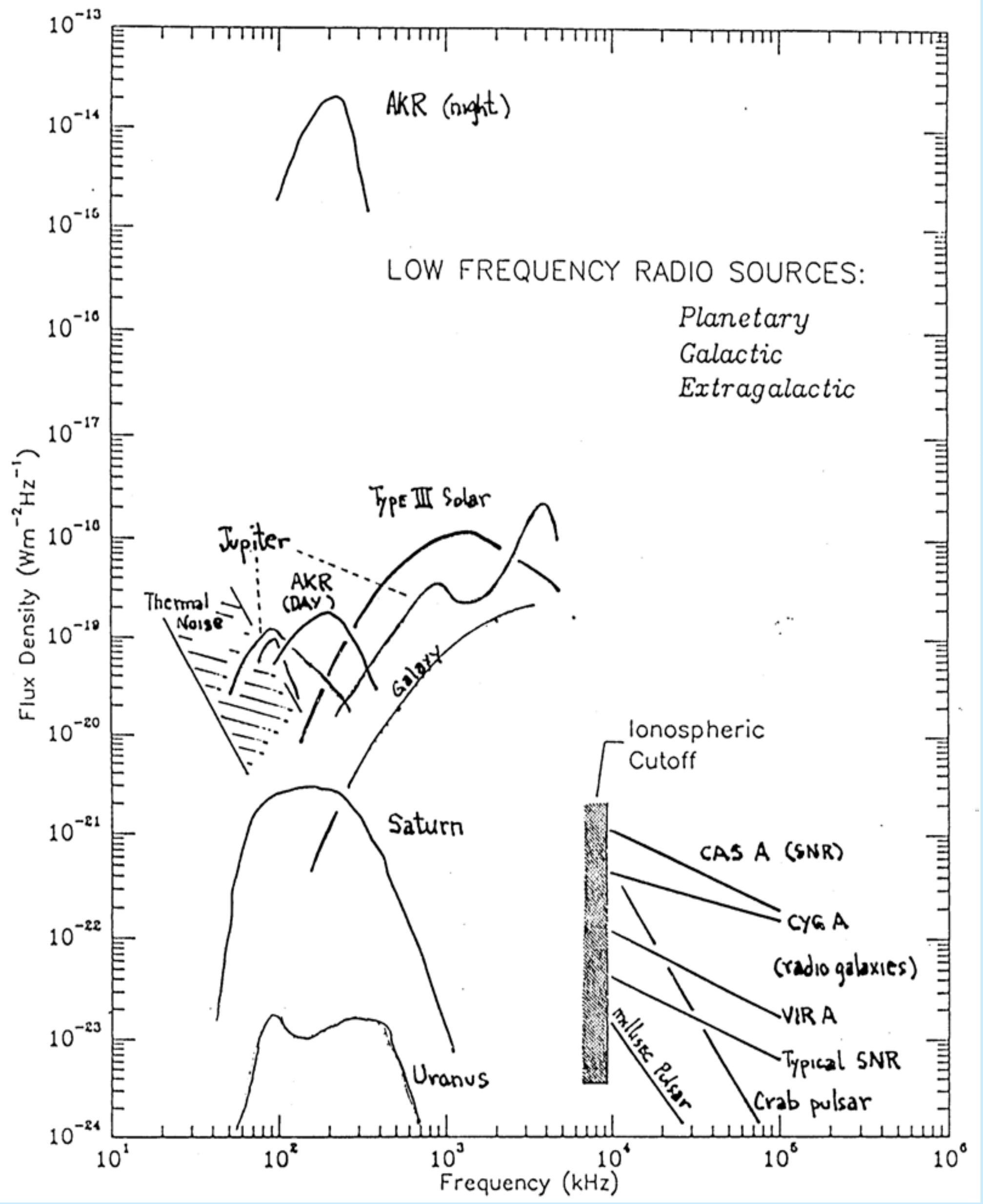



courtesy C. Carilli

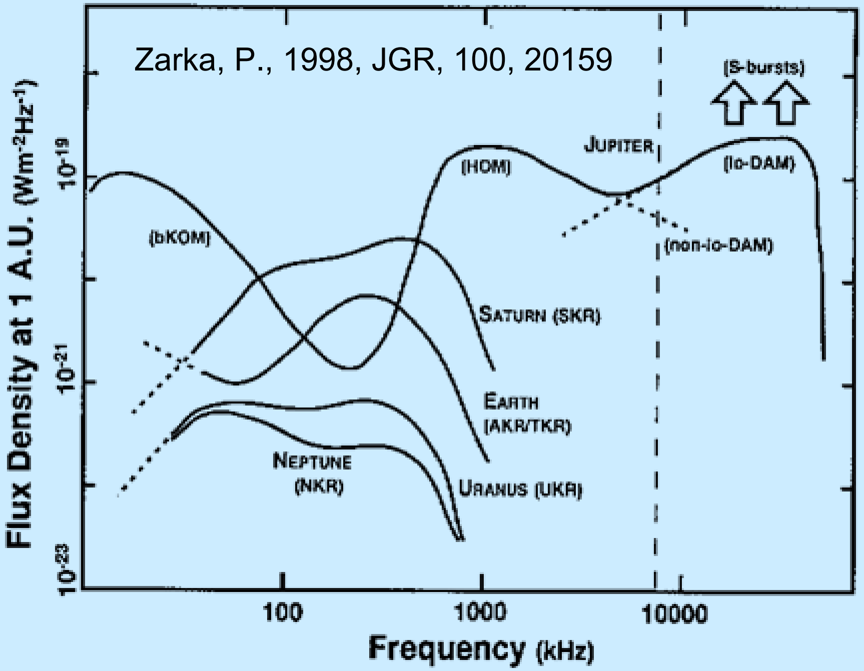
# Advantages to Radio Observations from the Moon

- No interference from radio/TV broadcasting.
- No atmospheric distortions.
- Ability to observe the universe at ultra low-frequencies (<15 MHz, redshifts =100-1000) which are blocked by the ionosphere.

# Low Frequency Environment from the Moon

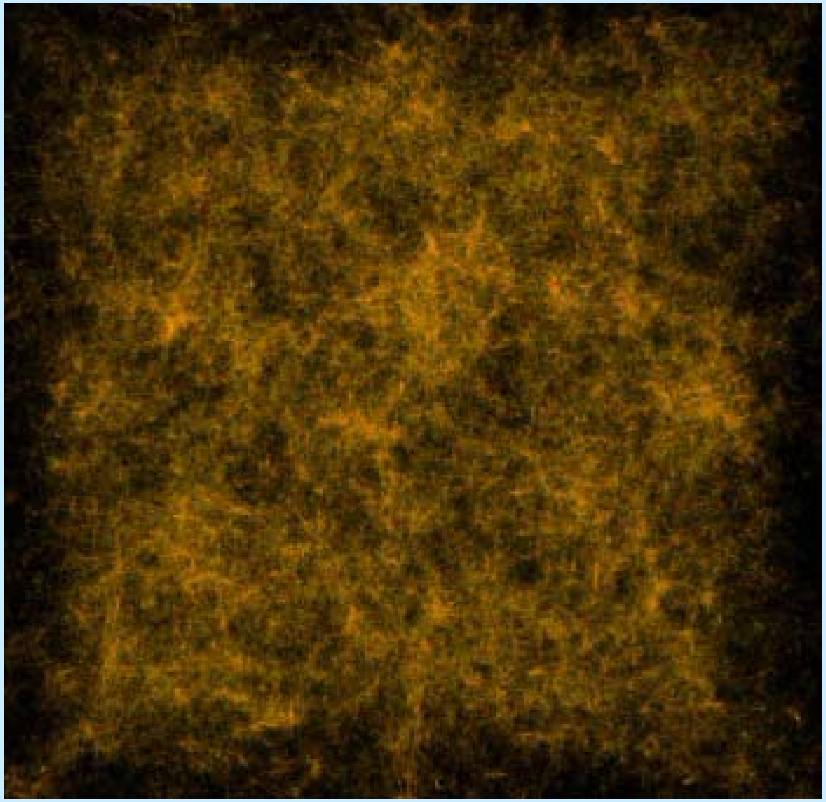



- >1 MHz interference is from Earth ionospheric breakthrough.
- <1 MHz interference comes from Earth's auroral kilometric radiation (AKR) peaking at 200 kHz.
- Cyclotron radiation from magnetospheres of all the planets at 100's of KHz.
- Type III solar bursts.
- Milky Way becomes opaque at <2 MHz.



# Exciting Science at Long Radio Wavelengths

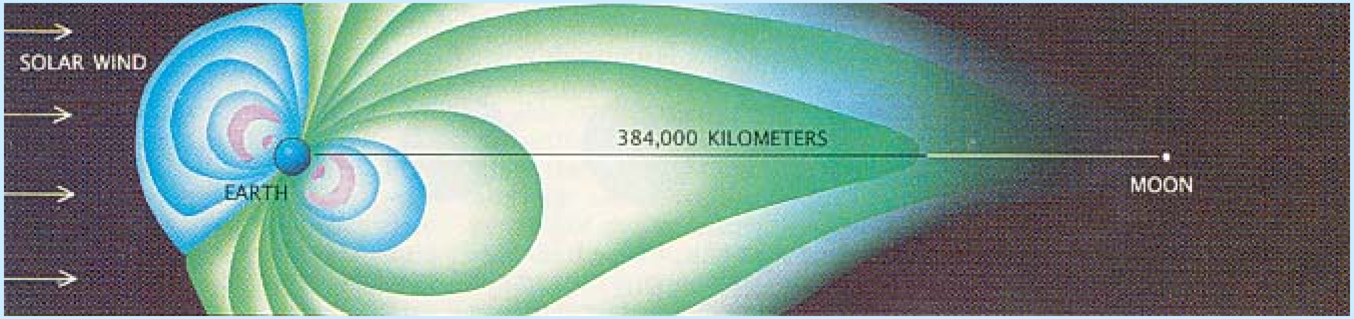
Baryons in z=10 universe from simulations (E. Hallman)



• ***Epoch of Reionization*** – When was "first light" in the Universe? Epoch of formation of the first sources of ionizing radiation from redshifted HI in emission and absorption (z = 6-50).

• ***Extrasolar Planets –*** Can modulated electron cyclotron emission from extra-solar planets be detected at low frequencies?

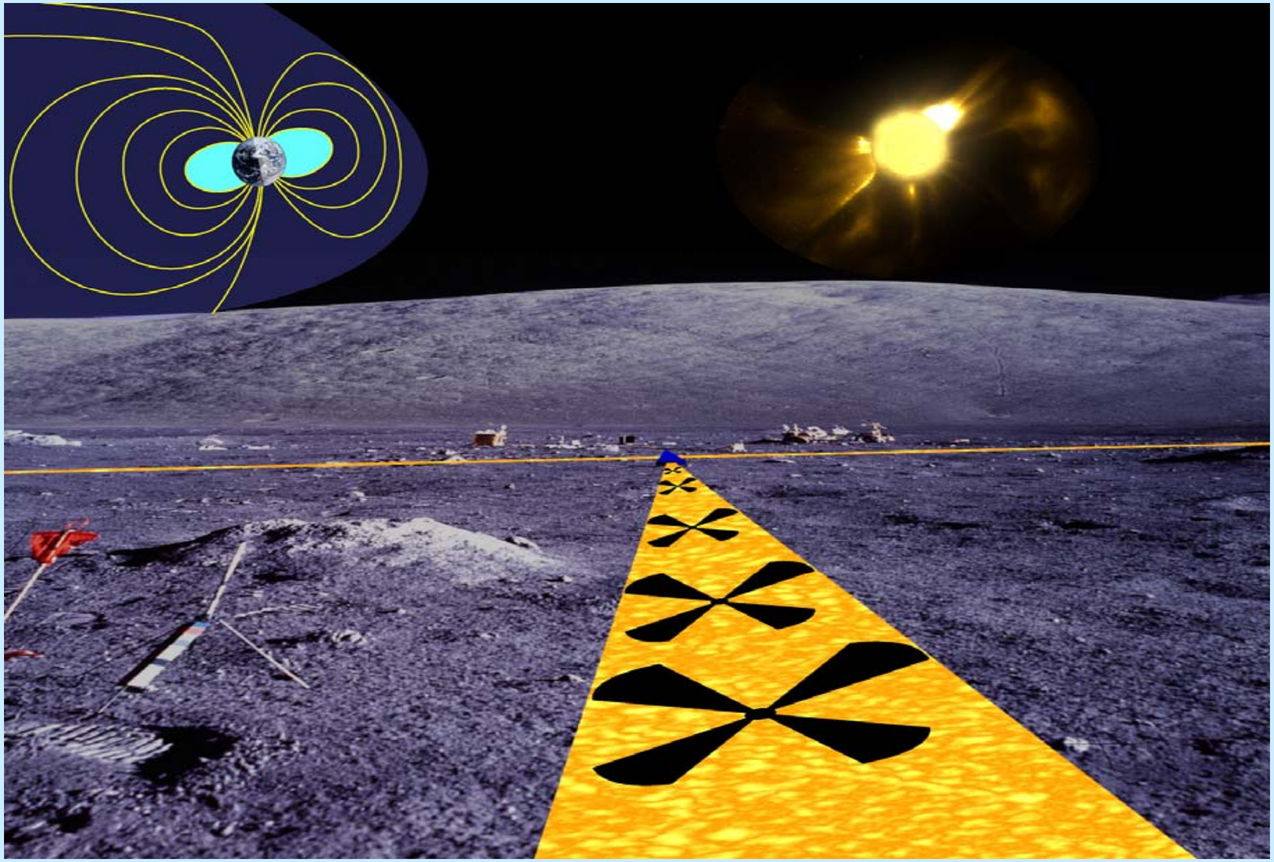
• ***Particle Acceleration –*** What are the low energy "seeds" from which the highest energy particles result?



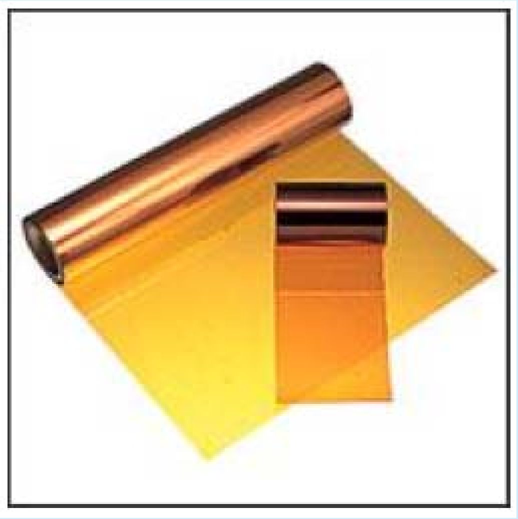
# ROLSS: Radio Observatory for Lunar Science Sortie

J. Lazio & K. Weiler, NRL; R. MacDowell, L. Demaio, N. Gopalswamy, & N. Kaiser, GSFC;
J. Burns, U. Colorado; D. Jones, JPL; S. Bale, U.C.-Berkeley; J. Kasper, MIT

- A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km) targeting EoR, extrasolar planets, etc. -- interferometers grow as you go.
- Operating at 1-10 MHz (30-300 m), produces factor of 10 increase in resolution (<2º at 10 MHz) and sensitivity over previous space missions (e.g., RAE).
- Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.

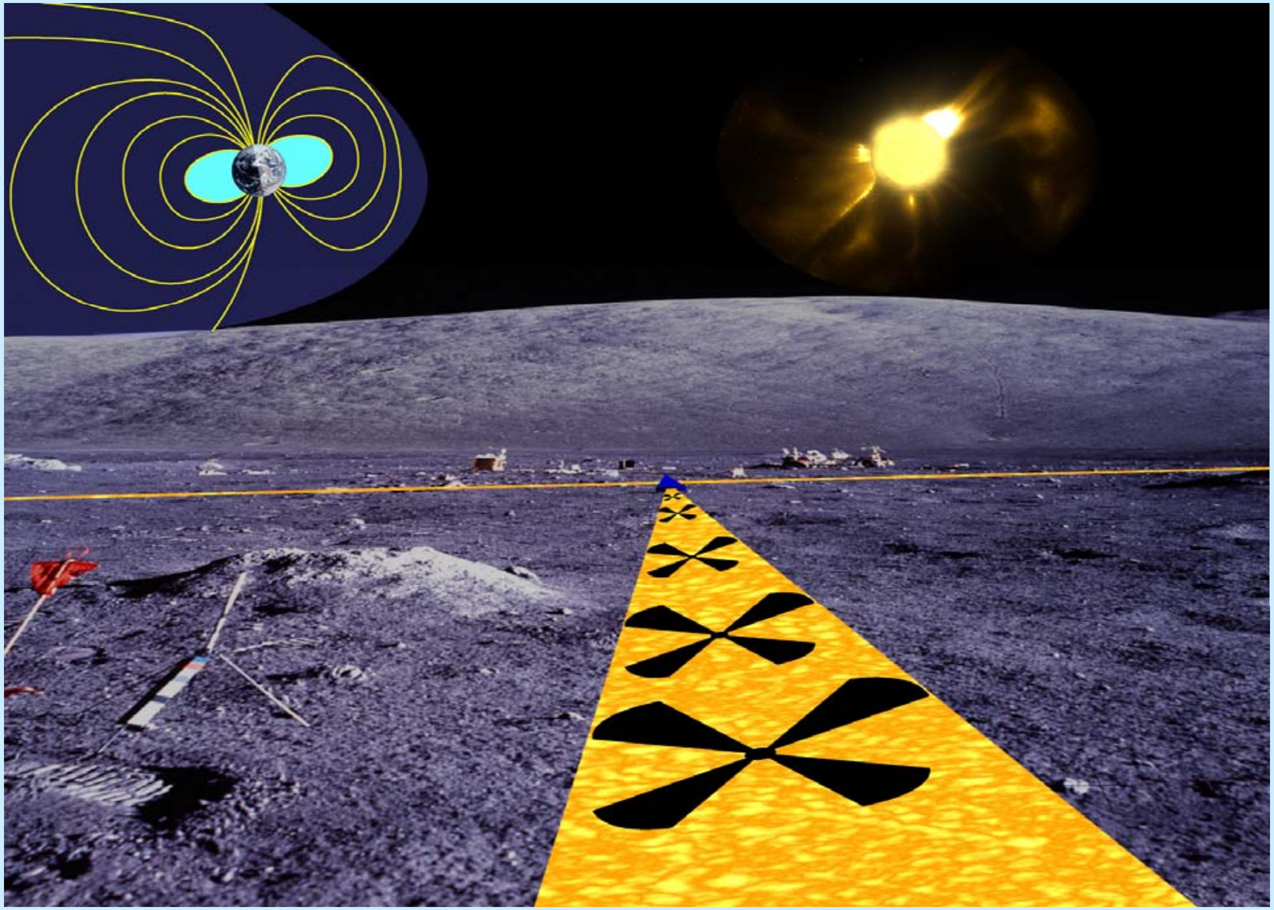


- Arms are a thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).

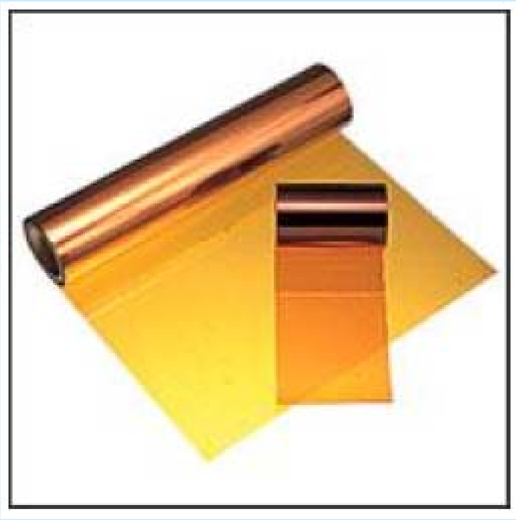


# ROLSS: Radio Observatory for Lunar Science Sortie

- 2 receivers per antenna; initial amplification & A/D conversation on the Moon.
- Digitized filtered signals transmitted to ground and correlated in software.
- 10 cm x 10 cm downlink antenna at 26 GHz; only needs 1.6 W of power.
- Data rate is 5 MB/sec.



- Dupont Kapton film is high grade insulation material with high heat durability.



# Asking for the Moon

**Thanks to several upcoming robotic missions, lunar science is poised for its biggest boost in a generation. But NASA managers have made it clear that research will be the tail on the exploration dog**

TEMPE, ARIZONA—Fashion isn't restricted to Paris runways. A decade ago, space scientists became enamored with the possibility of past life on Mars. More recently, moons such as Europa, Titan, and Enceladus captured the imagination of researchers. Soon, Earth's only satellite will get a chance to strut her stuff again, after being out of style for more than 3 decades. Four countries—Japan, India, China, and the United States—are preparing to launch robotic lunar probes in the next 18 months. China is planning a human mission, and NASA is pushing ahead with plans for a human outpost by the end of the next decade based on a 2004 vision laid down by President George W. Bush.

With the moon back in the footlights, the question for U.S. scientists is whether lunar science can sustain funding for a long-term research program. Science has always played second fiddle to engineering human flight at NASA, and the new exploration program is no exception. As NASA Administrator Michael Griffin bluntly told the 250 scientists who gathered here last week at the request of NASA's Advisory Council, a return to the moon "is not all about you." If scientists want a dedicated human research sortie, he added, they'll need to find the $2 billion or so it would cost.

That message, along with NASA's recent decision to shelve a series of lunar robotic missions, stunned some participants. "The rather pessimistic view of lunar science outlined by Mike Griffin," says Brown University geologist Carle Pieters, left her "depressed and discouraged." Yet she and other scientists say they want to be involved in lunar planning. A weeklong session generated a long list of intriguing projects to pursue, along with advance word from a National Research Council (NRC) panel now studying lunar science that its report would urge NASA to ramp up funding for such research. "We don't want to preclude what could be a fascinating scientific opportunity," says Neil Tyson, an astronomer at the American Museum of Natural History in New York City. "The ship is leaving the dock, and the question is whether we'll be on it."

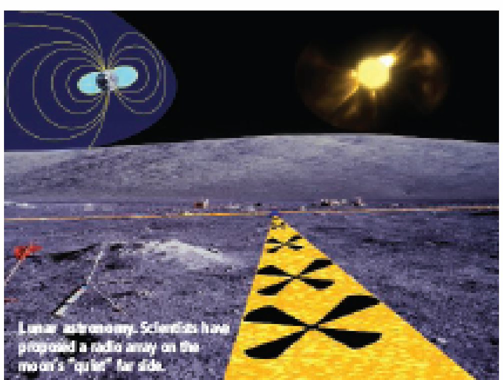
**Back to the future**

The gathering in Tempe hearkened back to a 1965 meeting on Massachusetts's Cape Cod that gave researchers an opportunity to inject scientific research into the Apollo program. Harrison Schmitt, a geologist who went on to become the first and only scientist to visit the moon and now chairs the agency's advisory council, was so impressed by the meeting that he asked NASA to repeat it. Schmitt says he overcame NASA's initial resistance by arguing that it needed a clear set of scientific priorities.

The early days of lunar science benefited greatly from the Cold War race to the moon. The United States and the Soviet Union sent more than 60 robotic missions—crash landers, soft landers, orbiters, sample returns—between 1958 and 1976. And that 18-year tally doesn't count the nine piloted Apollo flights that circled or landed on the lunar surface. By contrast, only four missions have visited the moon in the last 31 years.

Scientists still know remarkably little about Earth's satellite. Pressing scientific questions include why the moon's magnetic field appears to have shut off, how dust and plasma interact near the surface, and the nature of hydrogen deposits at the poles. The Apollo soil samples are insufficiently diverse to answer fundamental geological questions because they were drawn largely from the maria in the mid-latitudes of the moon's near side. The solar system's largest hole—the Aitken Basin near the south pole—has yet to be explored, and Mars has been mapped more accurately than the moon's pockmarked surface, which contains clues to the extent and timing of the heavy bombardment that shaped the early solar system. Like Greenland's ice cap, the moon's undisturbed layers preserve a long history—for example, a concise record of the sun's radiance over billions of years.

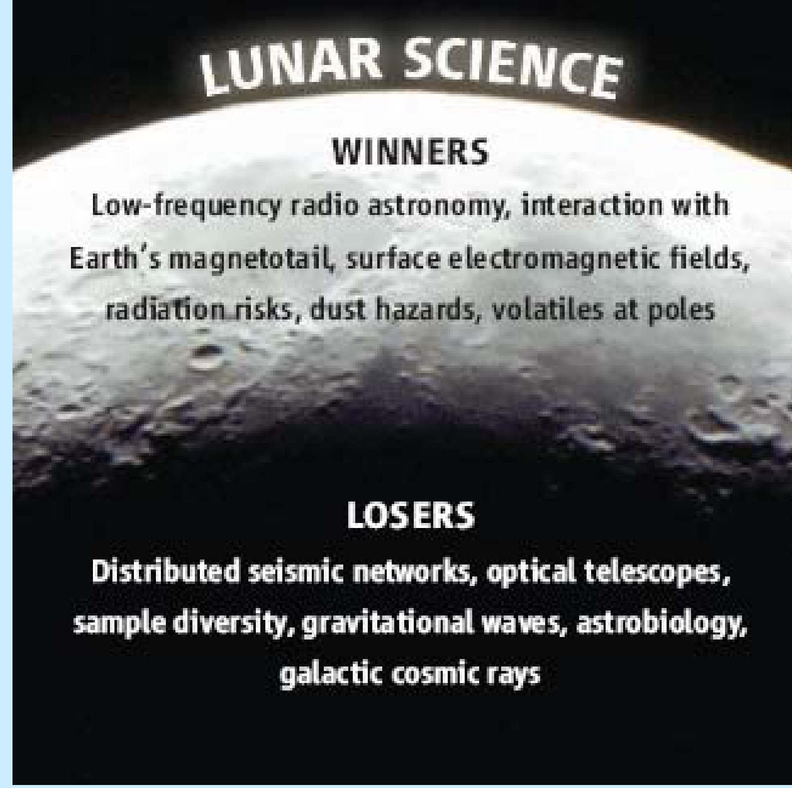
Scientists soon will have a shot at answering these and other questions. This year, Japan will launch a 3-ton, 14-sensor probe called Selene. China is completing work on Chang'e 1, which will examine the lunar crust and temperature and the space environment between Earth and the moon. Next year, India plans to send Chandrayaan-1,



Lunar astronomy. Scientists have proposed a radio array on the moon's "quiet" far side.

Old digs. Geologist Harrison Schmitt on the lunar surface during the last Apollo mission in December 1972.

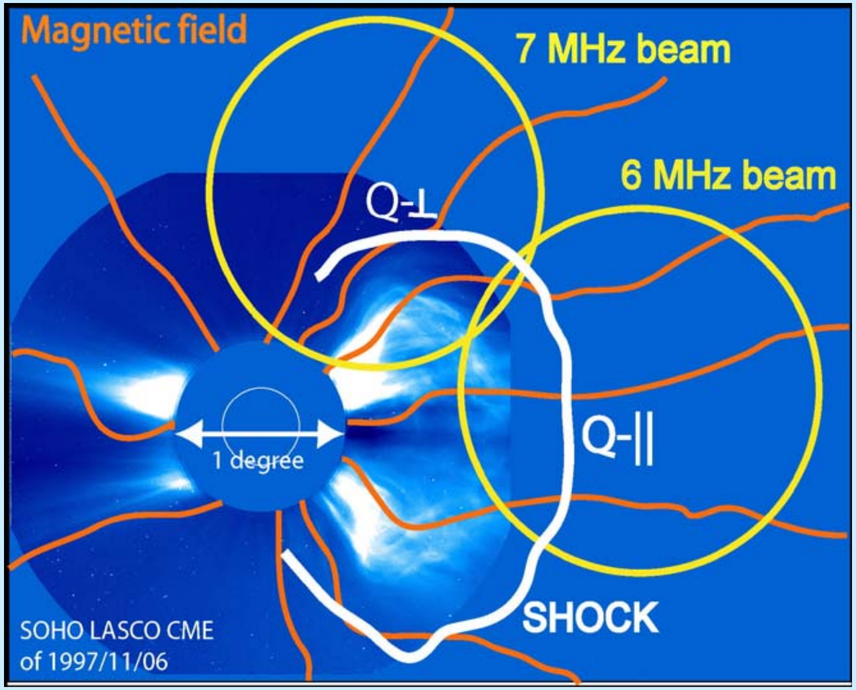




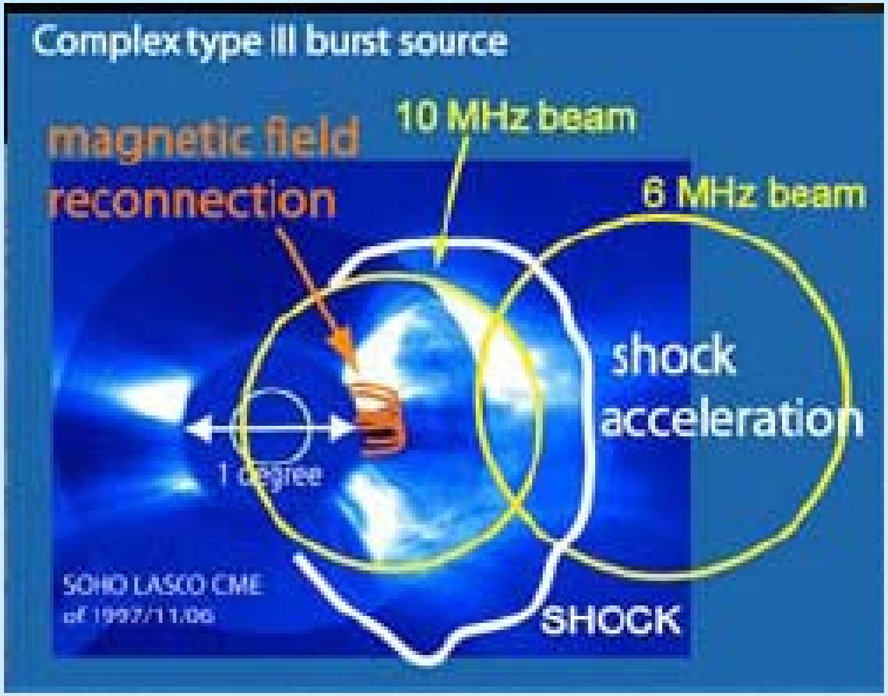

the solar wind, and a low-frequency radio observatory on the far side, in the quiet zone protected from noisy Earth. "This is the most exciting experiment which could be done from the surface of the moon," says Mario Livio, an astrophysicist at the Space Telescope Science Institute in Baltimore, Maryland.

***Science*, 16 March 2007**

# Solar Science with ROLSS




**Type II Burst source location**




**Complex Type III source location**

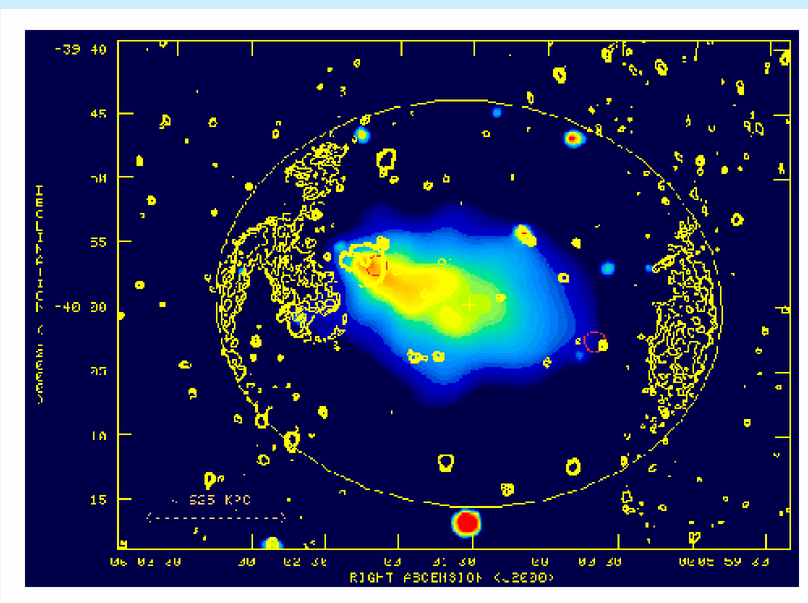
- ROLSS will produce the first high angular resolution (<2$^{o}$ at 10 MHz), high time resolution images of solar radio emissions (outer corona).
- ROLSS will determine source locations of coronal shock acceleration (Type II radio bursts) and magnetic field reconnection (Type III radio bursts).

# More Science with ROLSS: Shock Acceleration in Radio Galaxies

**VLA radio (green) image superimposed on optical image of the nearby radio galaxy Centaurus-A (Clarke & Burns).**

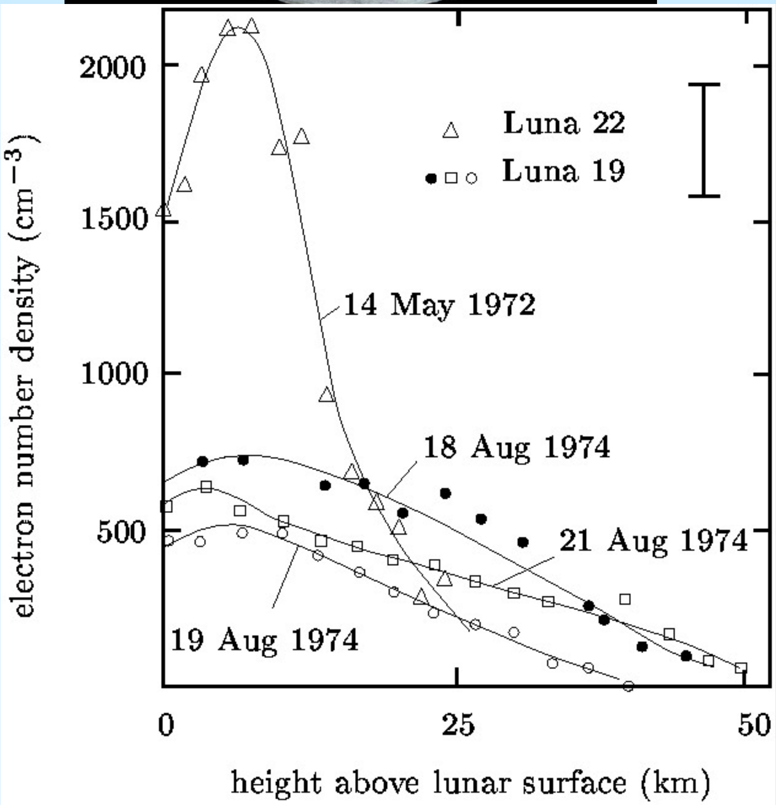
- For nearby, luminous radio galaxies such as Cen A, ROLSS will detect or set limits on the minimum electron energy (E<50 MeV).

- Diffusive shock acceleration believed to fail for $\gamma$<2000, corresponding to $\upsilon$=10 MHz for B=1 $\mu$G.



**Radio & X-ray emission from Large-scale shocks in the merging galaxy cluster Abell 3376 (Bagchi et al. 2006).**

# The Lunar Ionosphere



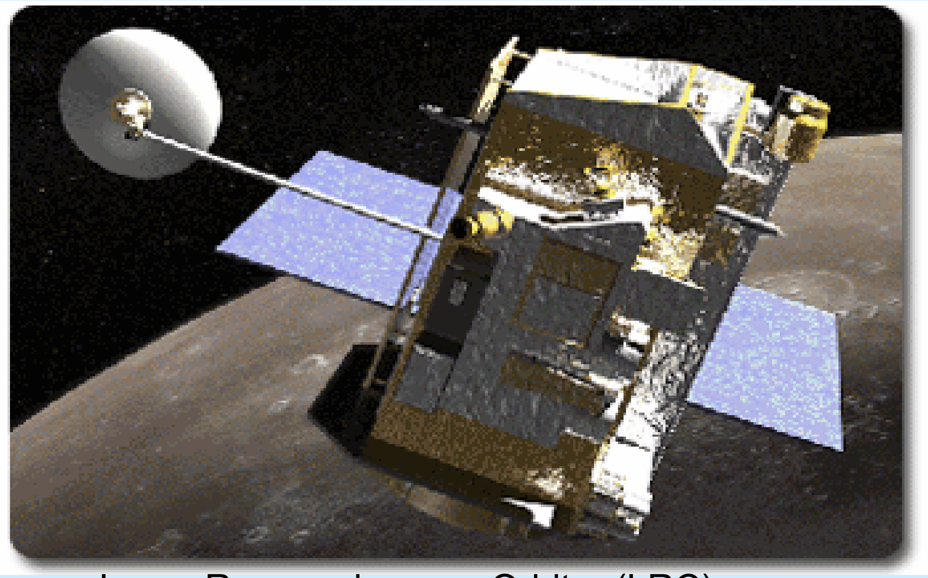

- Uncertainty about the density, geometry, & generation of a lunar ionosphere.
- A lunar atmosphere would have environmental implications for crewed operations on the Moon.
- Radio waves don't penetrate below the plasma frequency (9 kHz $\sqrt{n_e}$). Range of densities (100 to 5 x $10^4$ $cm^{-3}$) imply frequencies 90 kHz - 2 MHz.

ROLSS will use background Type III solar bursts to set limits on lunar ionospheric cutoff.

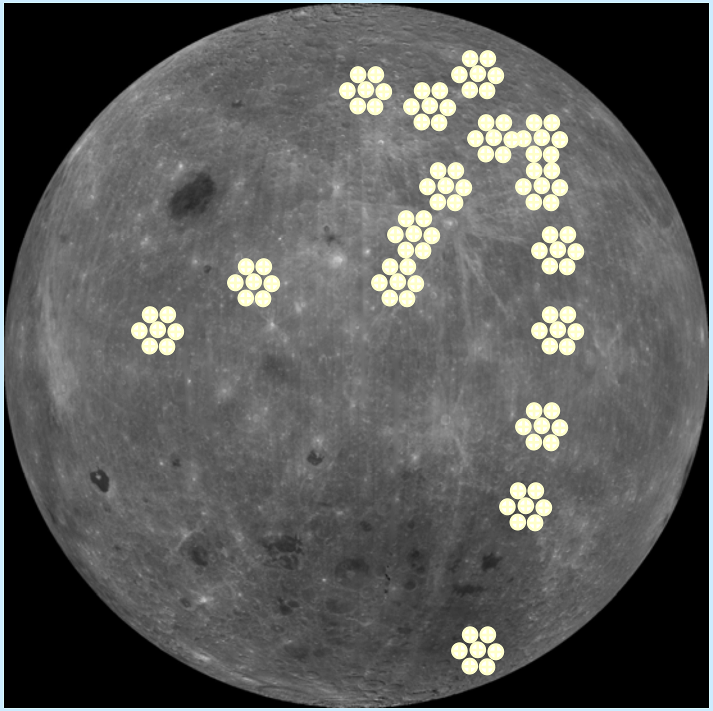
# Future

- Obvious expansion routes for ROLSS
  - Increase number of antennas/arms
  - Increase length of arms
  - Expand wavelength range
  - Move to far side
- All are necessary for exploring the Dark Ages and the Epoch of Reionization

  Dark Ages Lunar Interferometer (DALI)



Lunar Reconnaissance Orbiter (LRC)



**DALI = Dark Ages Lunar Interferometer**

# Challenges for a Lunar Farside Array

- An environmental impact assessment of Moon is needed before serious planning for lunar telescopes can be conducted.
- What are the properties of the lunar ionosphere? (Measure from orbit or with ROLSS).
- How bad is RFI on the Moon now and for the future?
- Diffraction limits – how far do we need to be on the lunar farside? (How sharp is the knife's edge?)
- Is a low power supercomputer needed for this array? (LOFAR is using an IBM Blue Gene with 0.15 MW).
- How cheaply can we build large collecting areas on the Moon?
- Can the radio instrumentation tolerate the lunar environment?