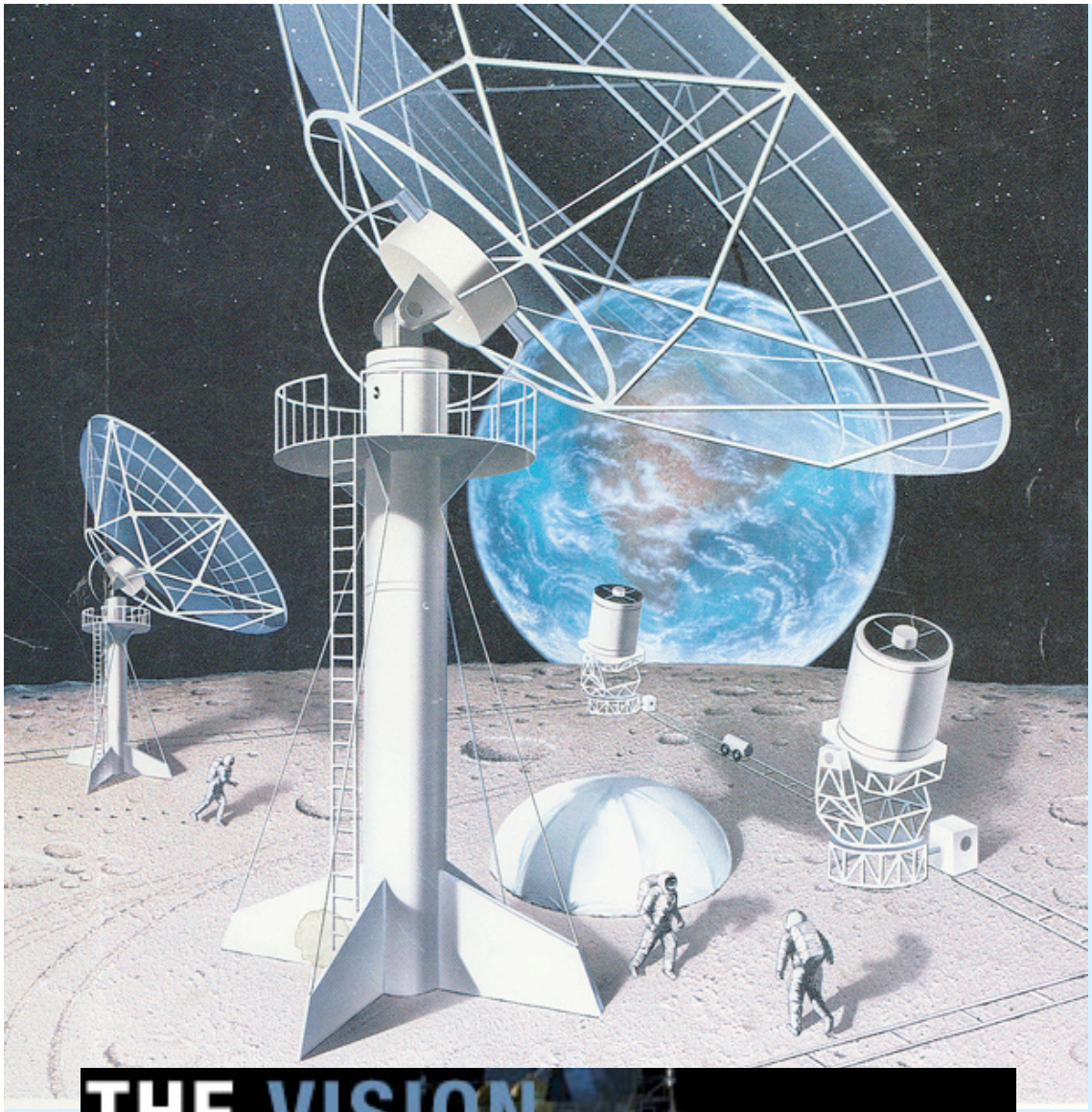


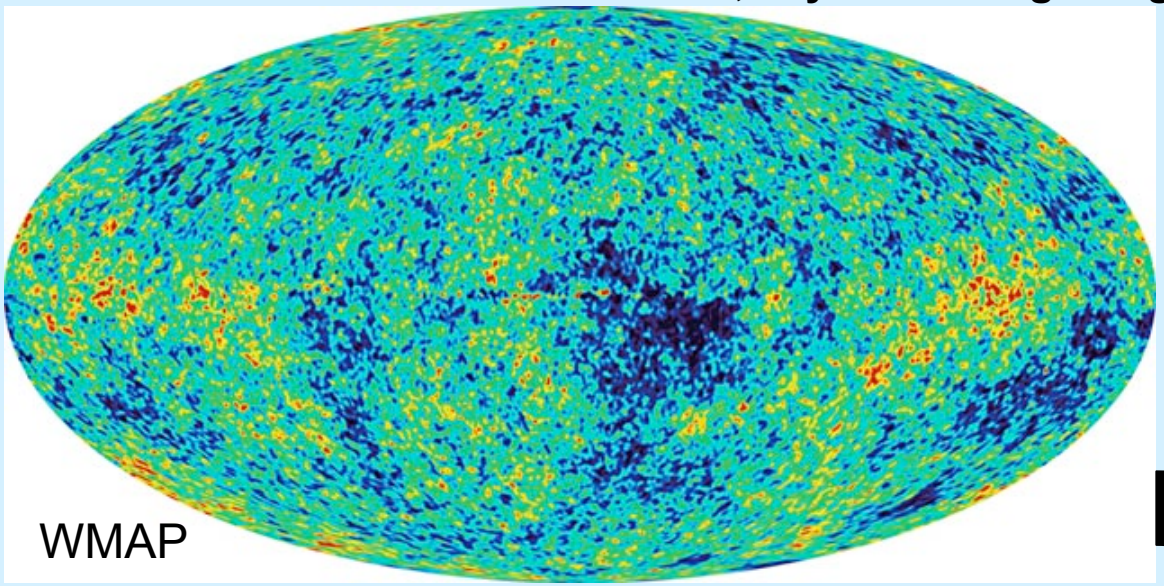
Probing Into the "Dark Ages" with a Low Frequency Interferometer on the Moon

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

Workshop on Science Associated with
the Lunar Exploration Architecture
February 28, 2007

From the CMB

400,00 yrs after Big Bang



WMAP

The Universe In Transition

Recombination (400,000 yrs)

The Dark Ages

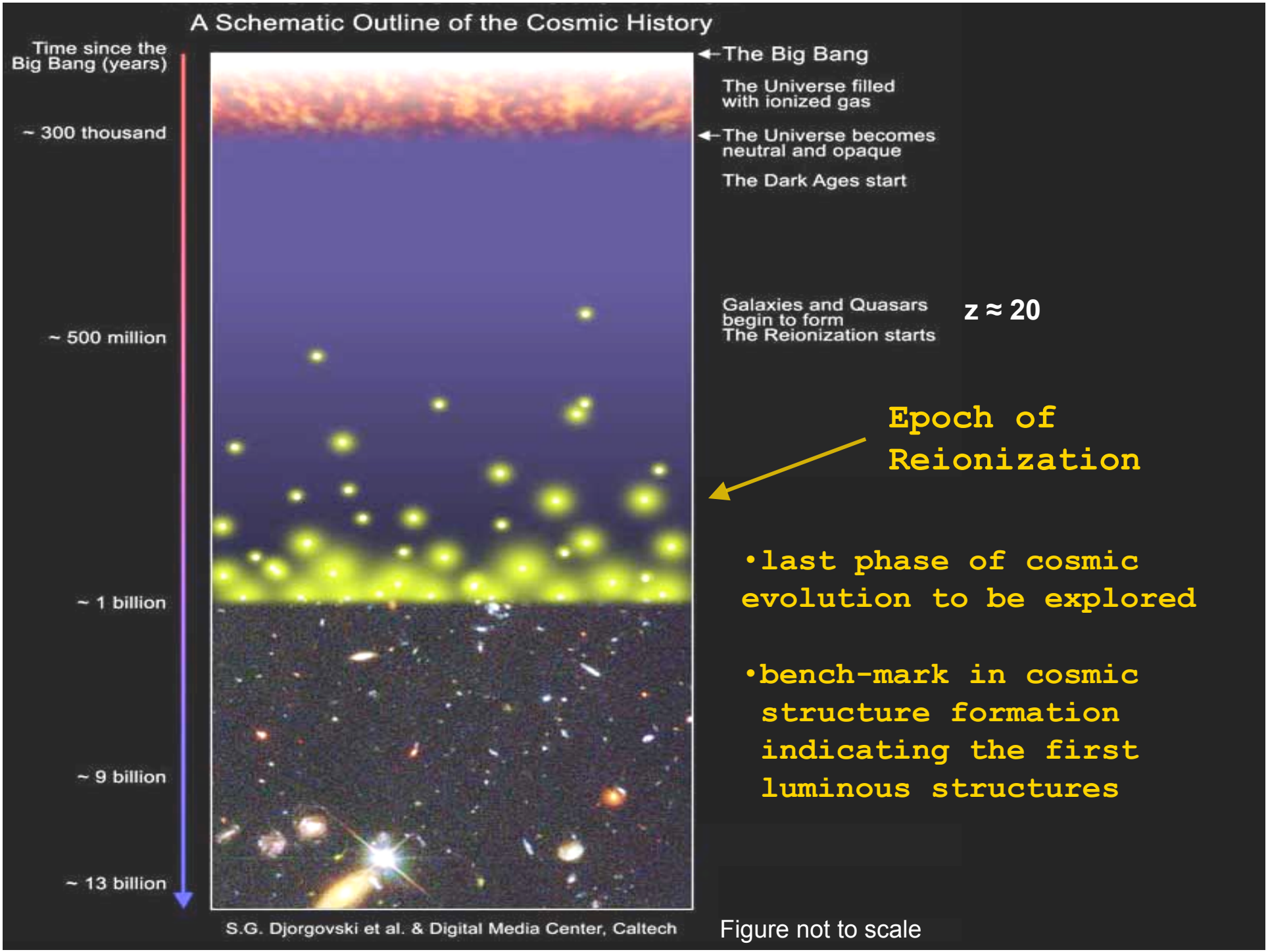
Reionization & 1st stars (10^8 yrs)

To

Today

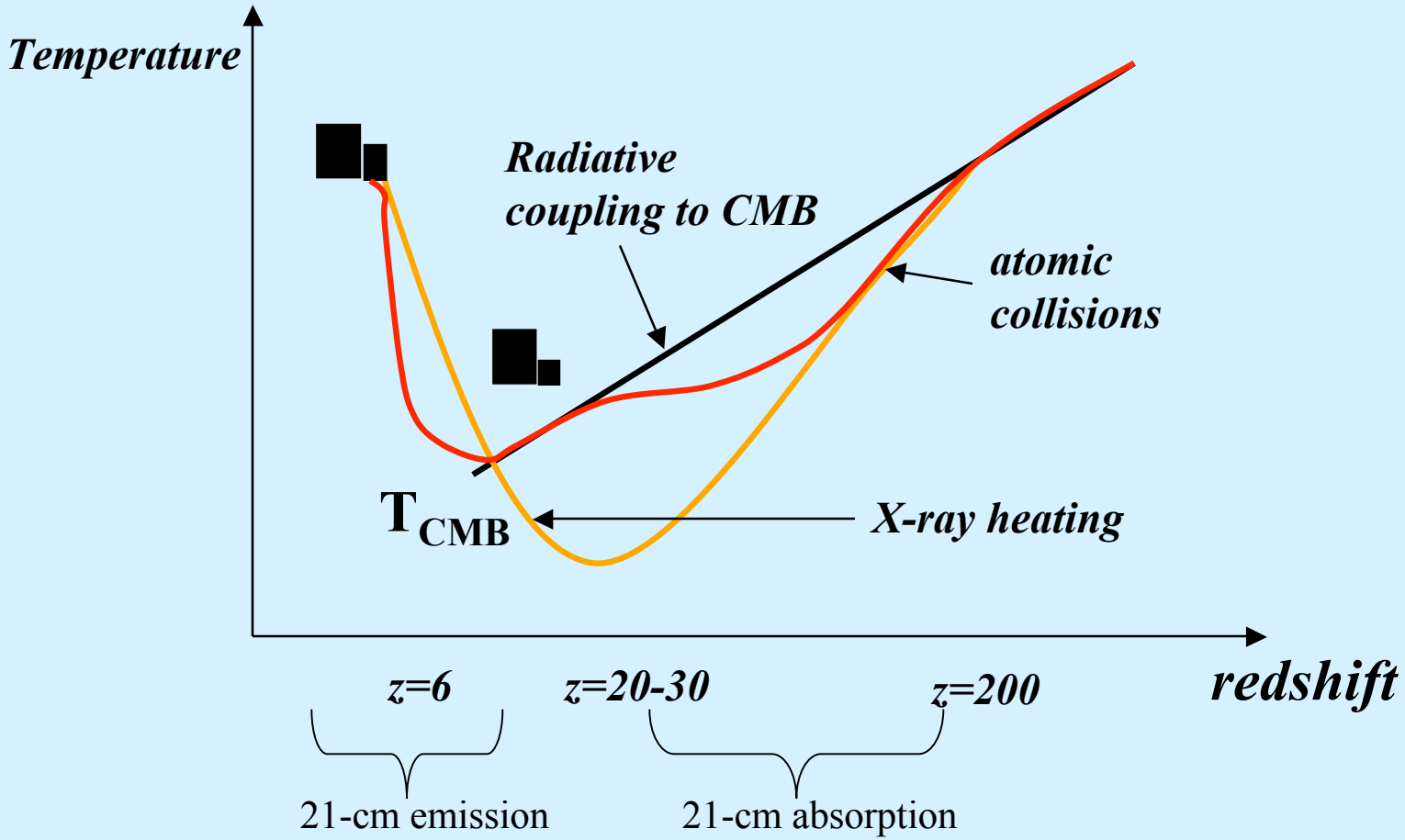
Clusters Of Galaxies

HST


A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
z ≈ 20
Epoch of Reionization
•last phase of cosmic evolution to be explored
•bench-mark in cosmic structure formation indicating the first luminous structures
S.G. Djorgovski et al. & Digital Media Center, Caltech
Figure not to scale

Thermal History

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



Sources of 21cm fluctuations

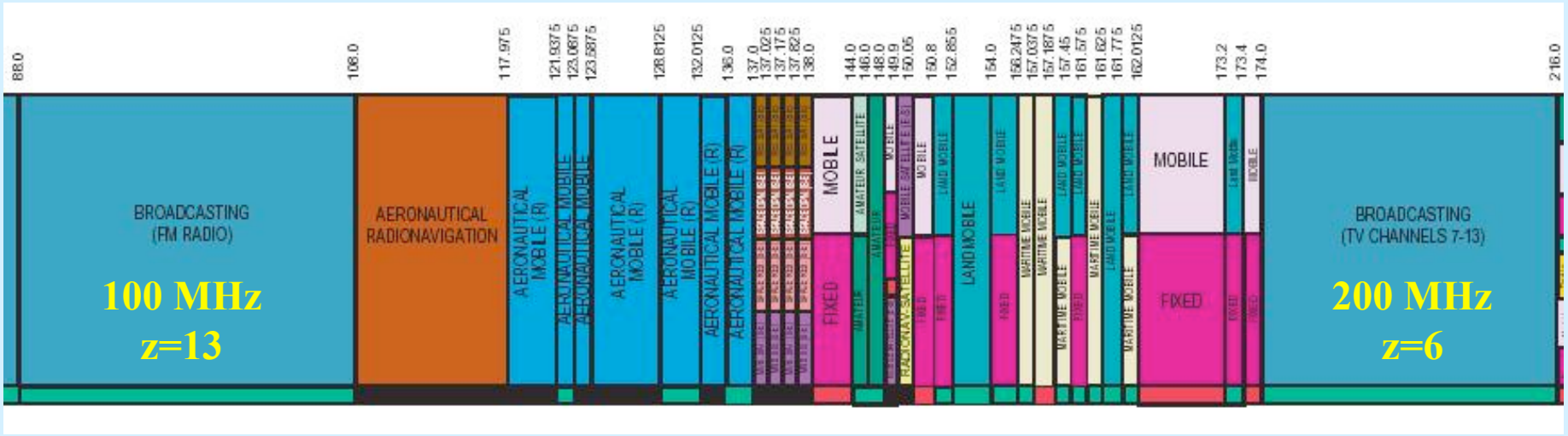
Density inhomogeneties (Loeb & Zaldarriaga 04) and peculiar velocities (Barkana & Loeb 04)
Ionized bubbles (Madau,Meiksin &Rees 1997;Furlanetto et al. 2004; Gnedin & Shaver 2003)
Emision from mini-halos (Iliev, Shapiro, et al. 2002)
Fluctuations in Lya flux, and gas temperature (Barkana & Loeb 2004)

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.

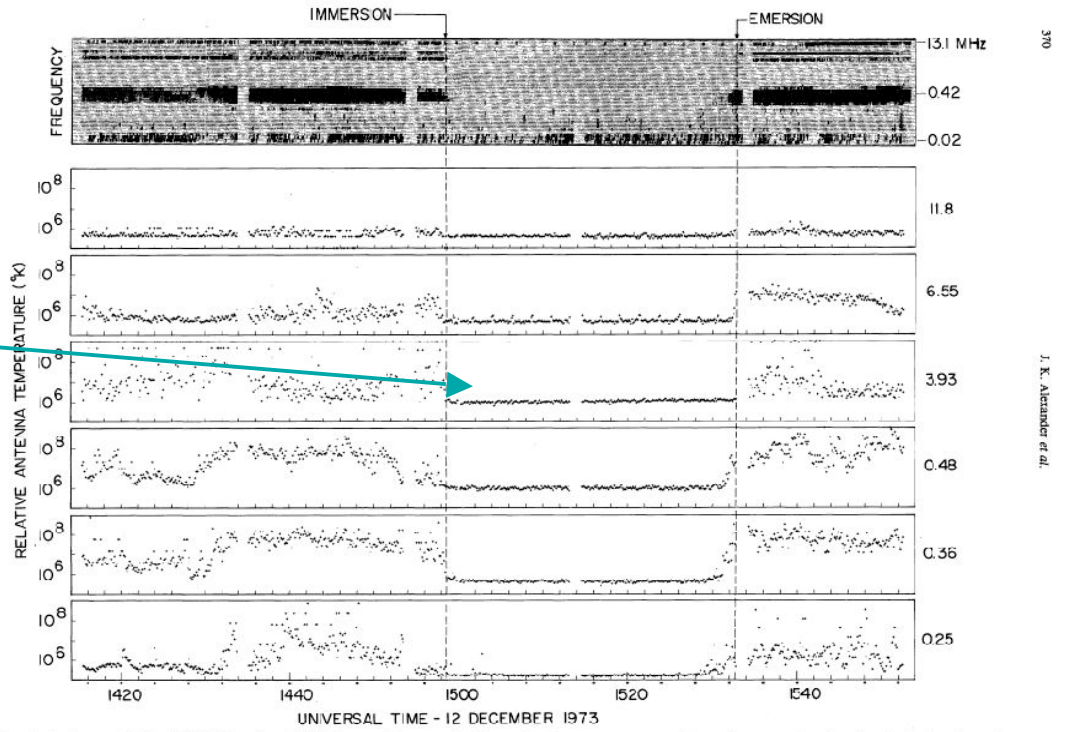
Lunar Advantage I: Interference

(courtesy C. Carilli, 2006)



Destination: Moon!

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 terrestial 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

370

J. K. Alexander et al.

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:

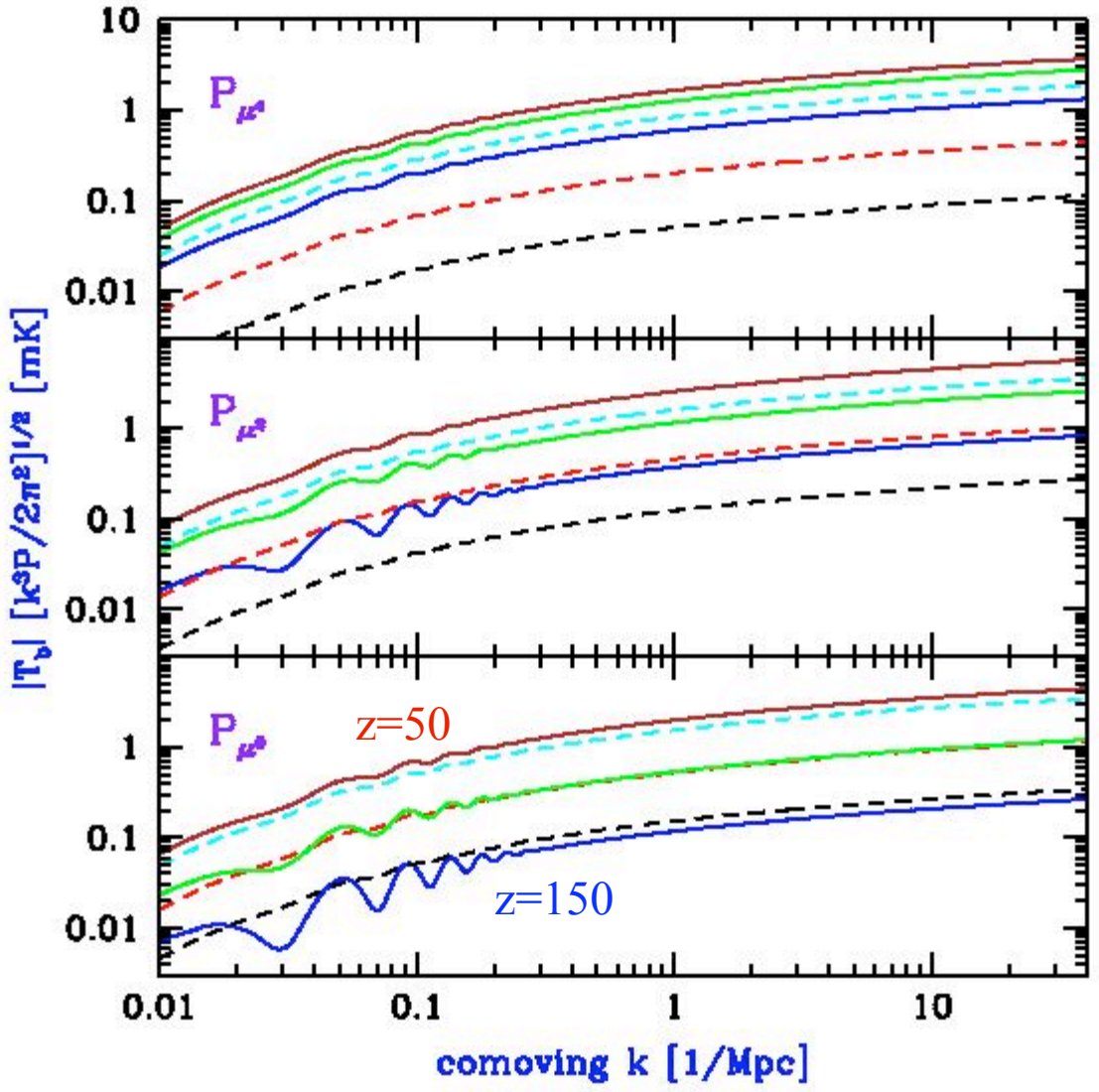
$T = 100(\nu/200\ MHz)^{-2.7}$ K

= 20,000K at 30MHz =>

rms = 0.2 mJy

Need > 10 SKAs
(but not in physical area!)

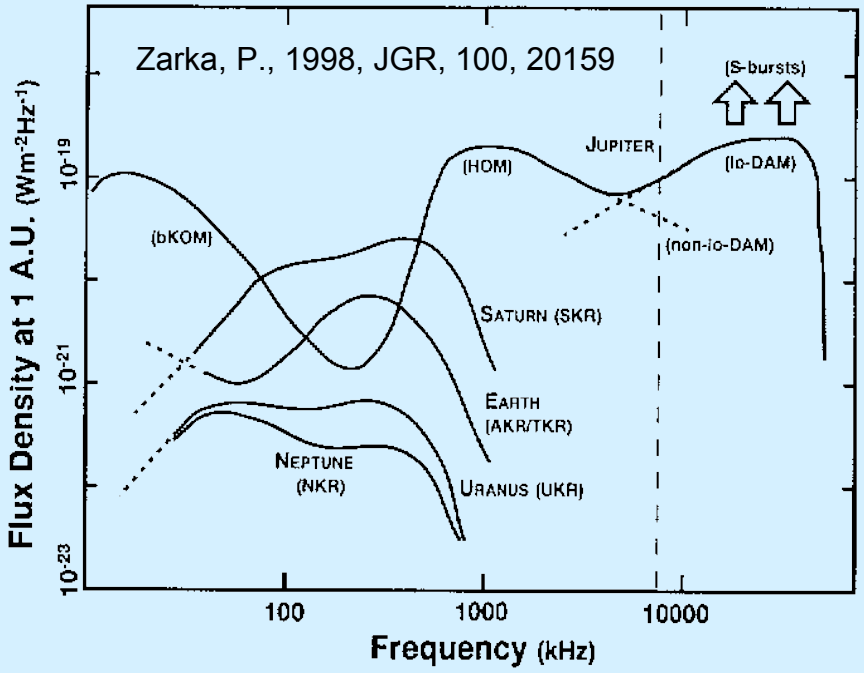
Need DNR > 10^6



courtesy C. Carilli

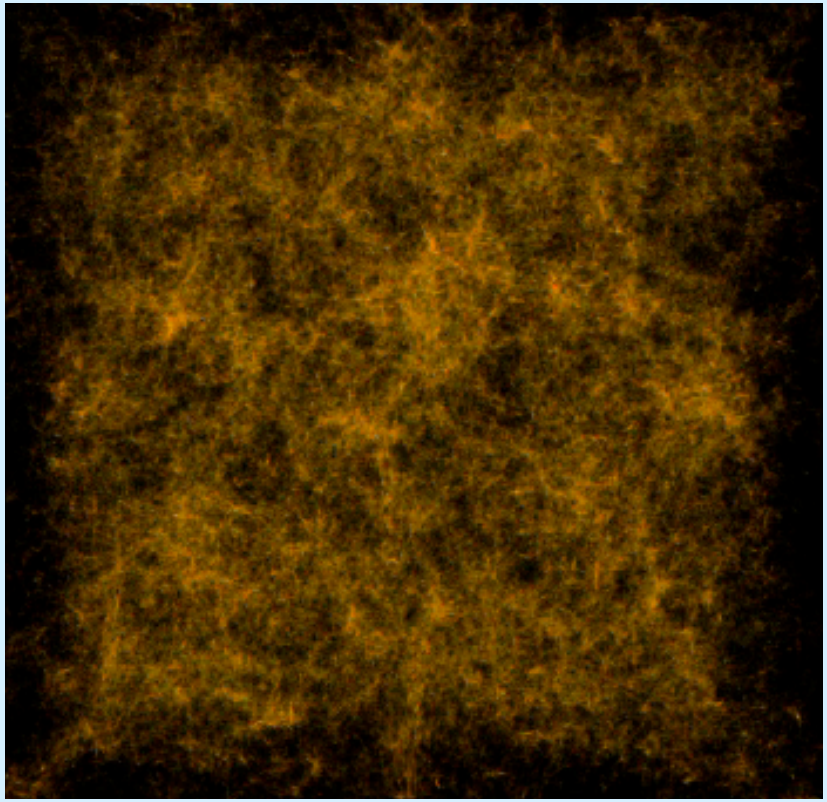
Low Frequency Environment from the Moon

- >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

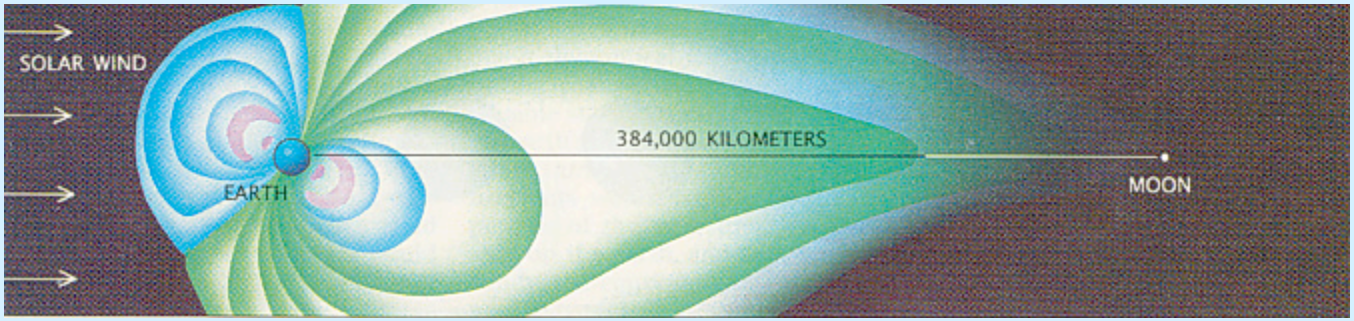
Baryons in z=10 universe from simulations



- ***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?

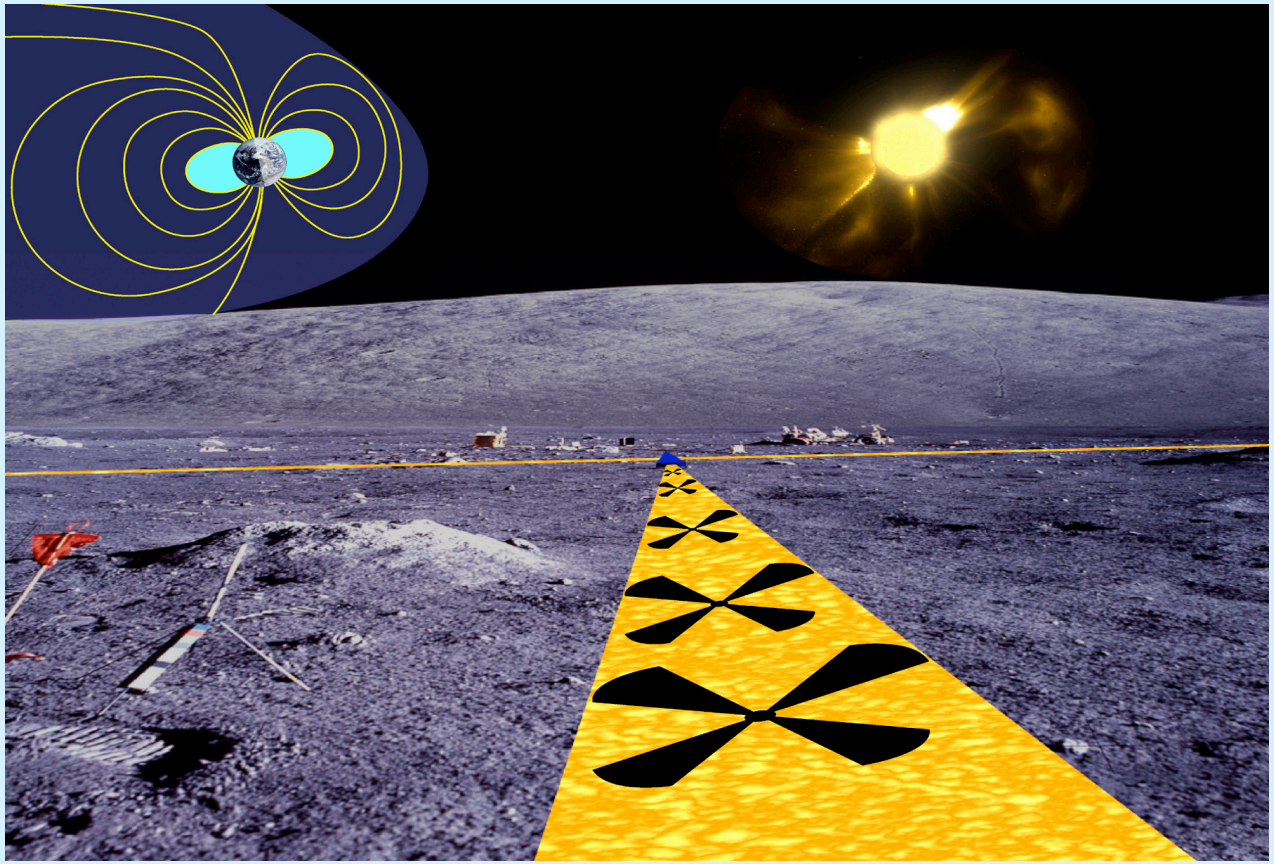
- ***Particle Acceleration –*** What are the low energy "seeds" from which the highest energy particles result?



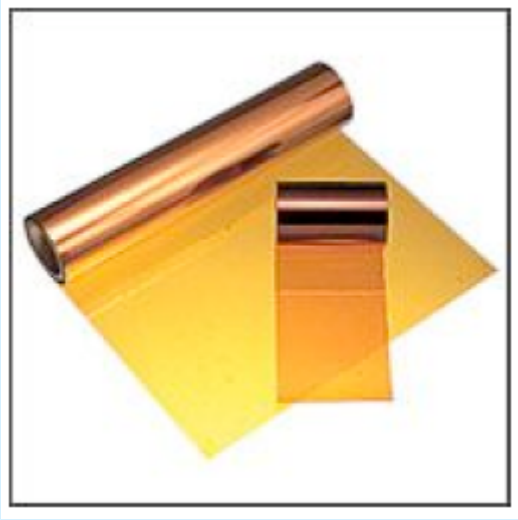
ROLSS: Radio Observatory for Lunar Science Sortie

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

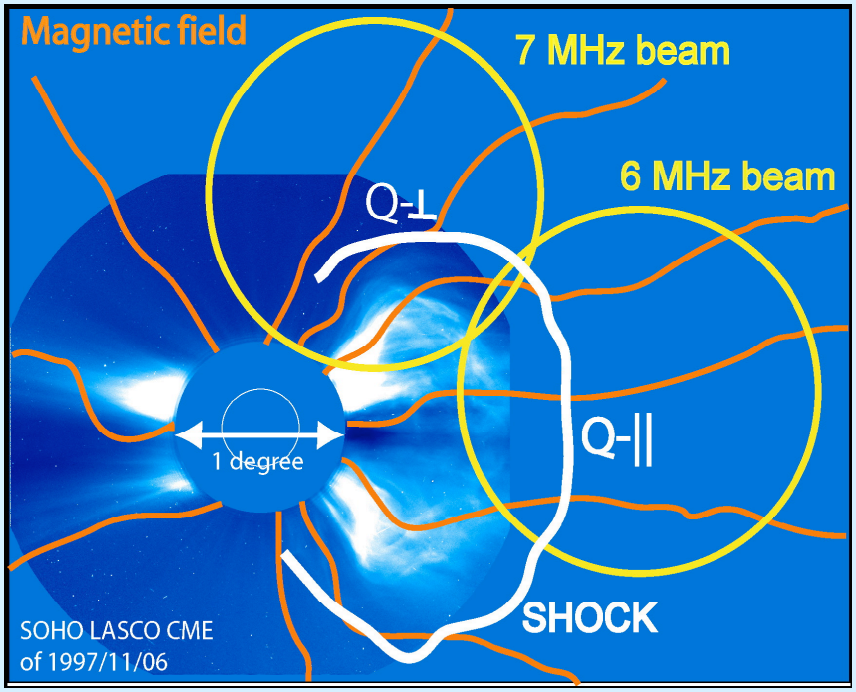
- A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km) targeting EoR, extrasolar planets, etc. -- interferometers grow as you go.
- Operating at 1-10 MHz (30-300 m), produces factor of 10 increase in resolution (<1° at 10 MHz) and sensitivity over previous space missions (e.g.,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



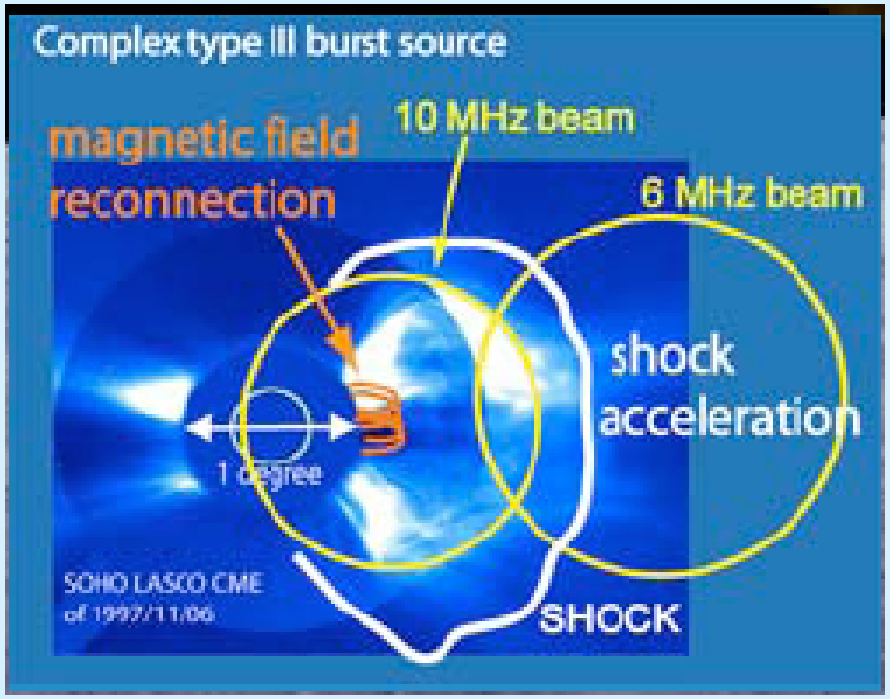
- Arms are a thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 thickness).



Solar Science with ROLSS



Type II Burst source location



Complex Type III source location

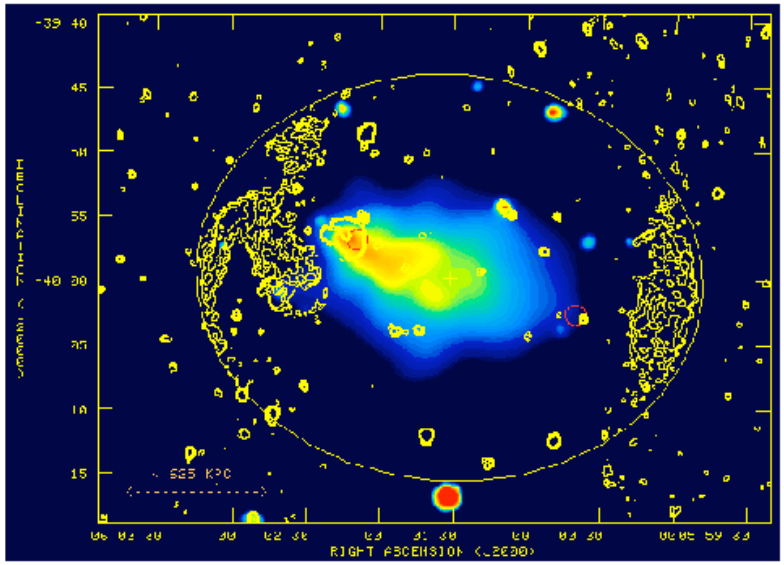
- ROLSS will produce the first high angular resolution (<1° at 10 MHz), high time resolution images of solar radio emissions (outer corona).
- ROLSS will determine source locations of coronal shock acceleration (Type II radio bursts) and magnetic field reconnection (Type III radio bursts).

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 γ<2000, corresponding to υ=10 MHz for B=1 μG.

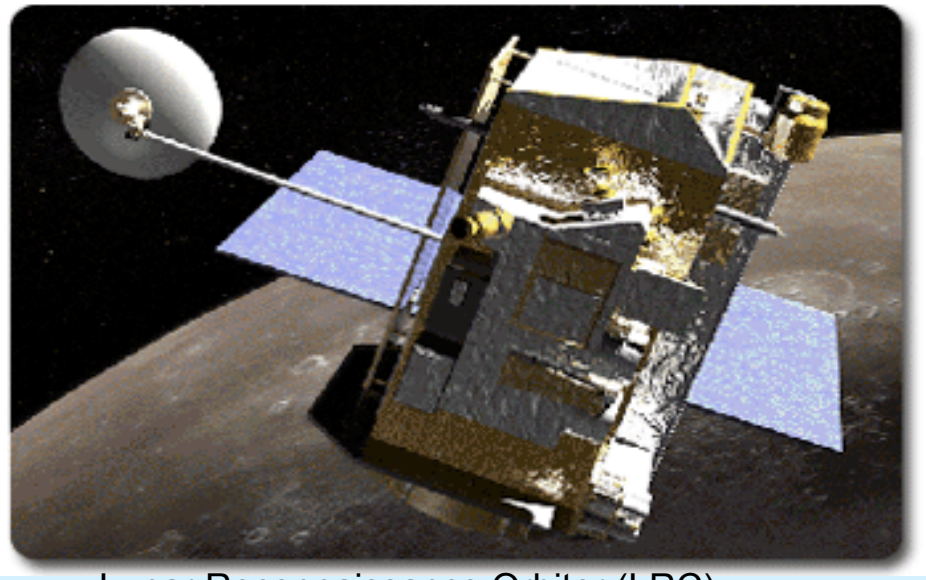


Radio & X-ray emission from Large-scale shocks in the merging galaxy cluster Abell 3376 (Bagchi et al. 2006).

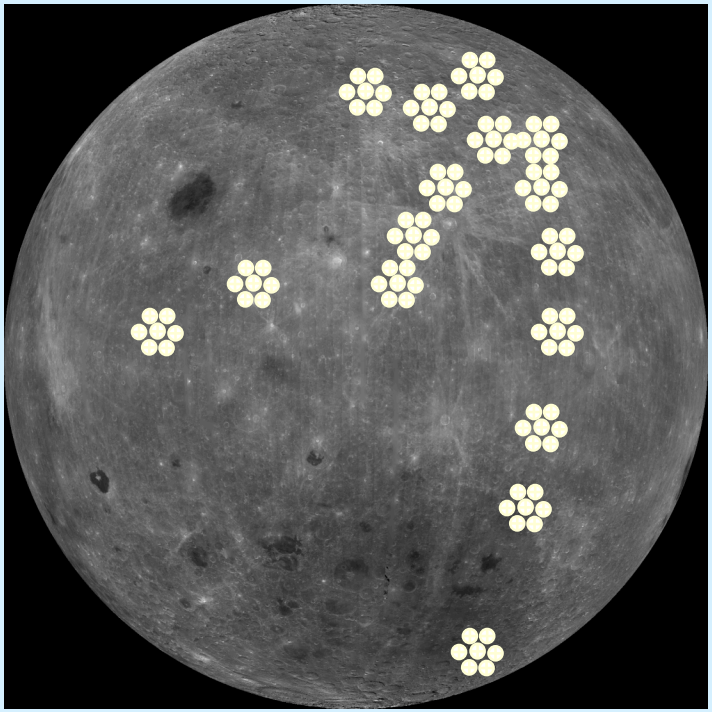
The Lunar Ionosphere

- 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.



Lunar Reconnaissance Orbiter (LRC)

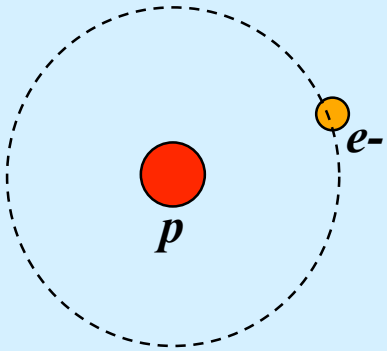


DALI = Dark Ages Lunar Interferometer

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?

Hydrogen



Ground level

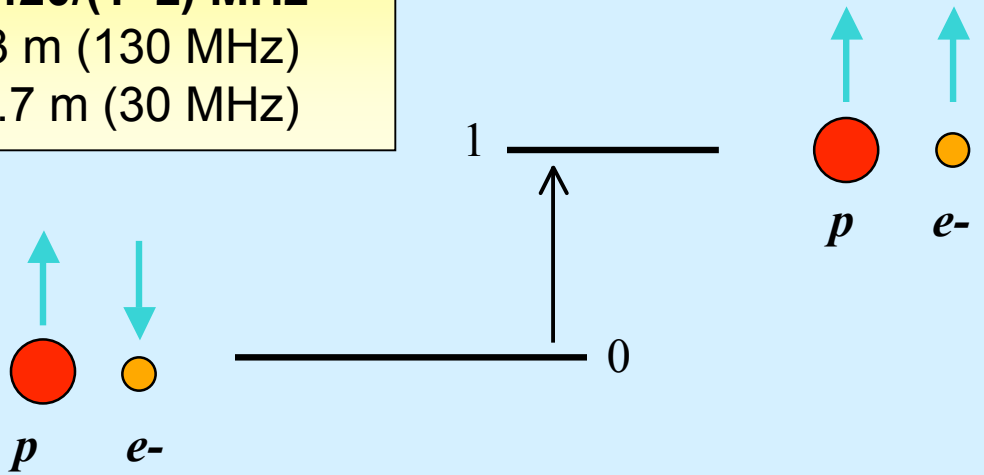
excitation rate= (atomic collisions)+(radiative coupling to CMB)

Couple ***to***

Couples ***to*** T_{CMB}

spin

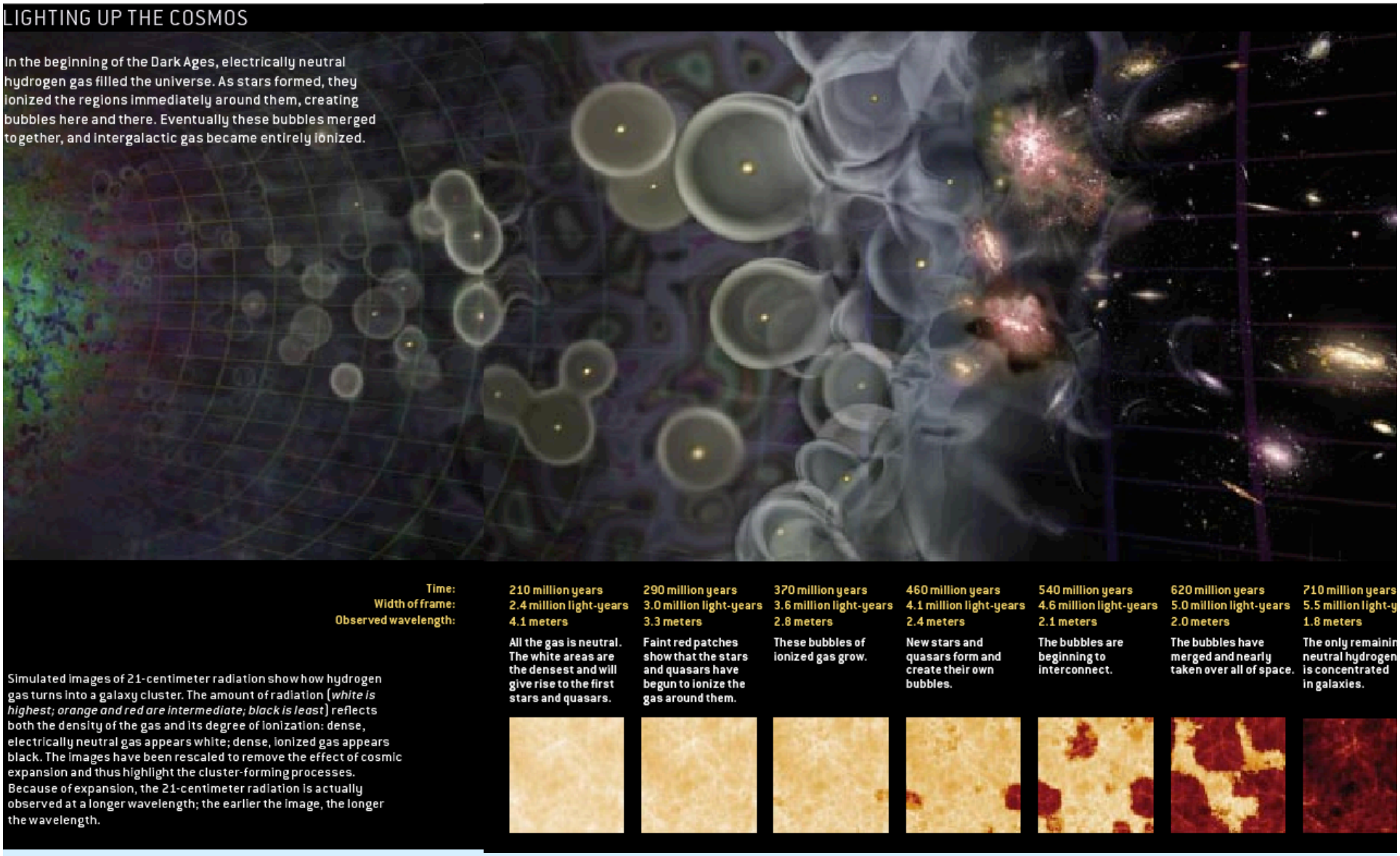
21 (1+z) cm = 1420/(1+z) MHz
At z=10, λ = 2.3 m (130 MHz)
At z=50, λ = 10.7 m (30 MHz)



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

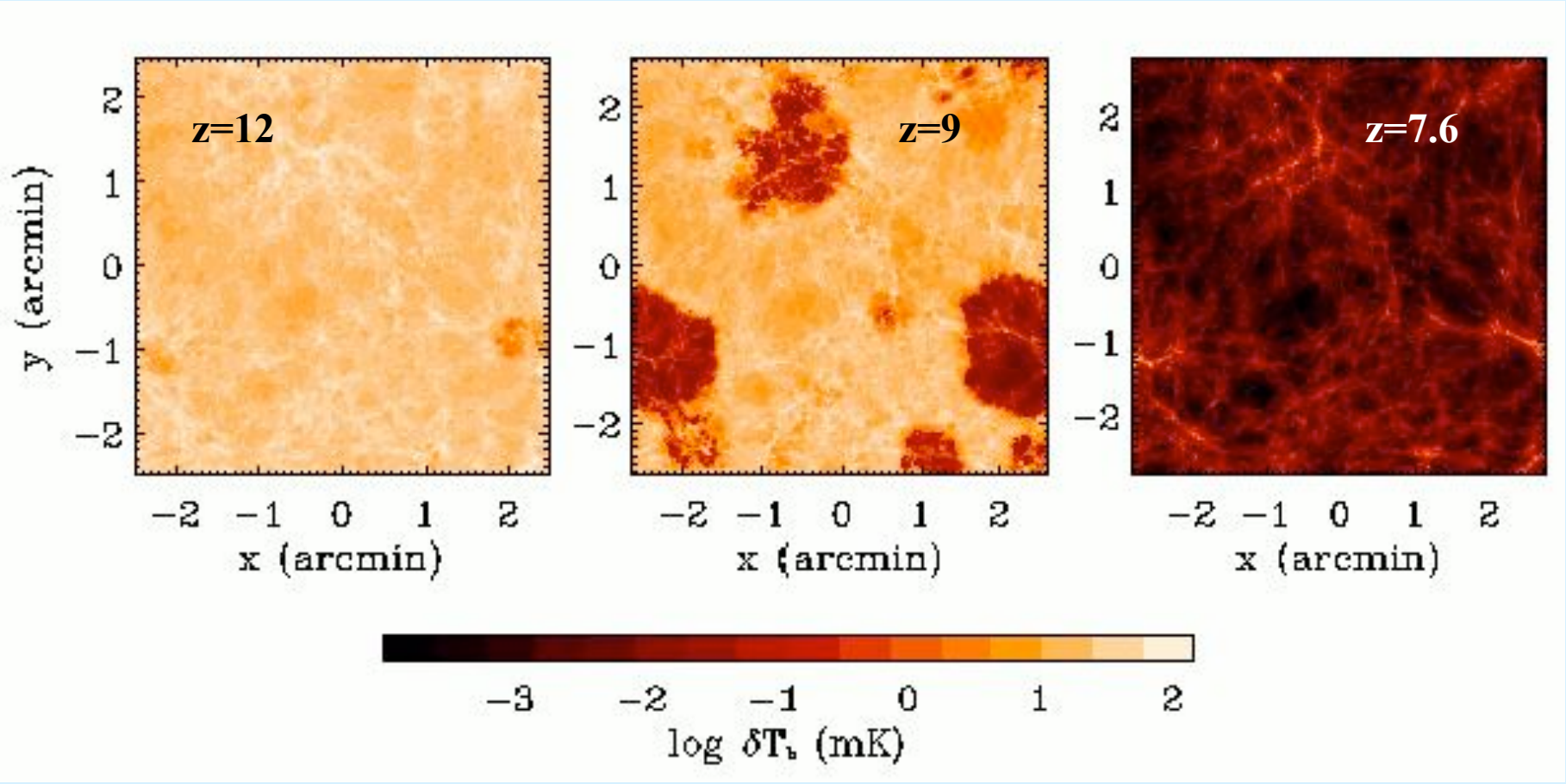
Predicted by Van de Hulst in 1944; Observed by Ewen &Purcell in 1951 at Harvard

A. Loeb, *Scientific American,* November 2006



HI 21cm Tomography of IGM

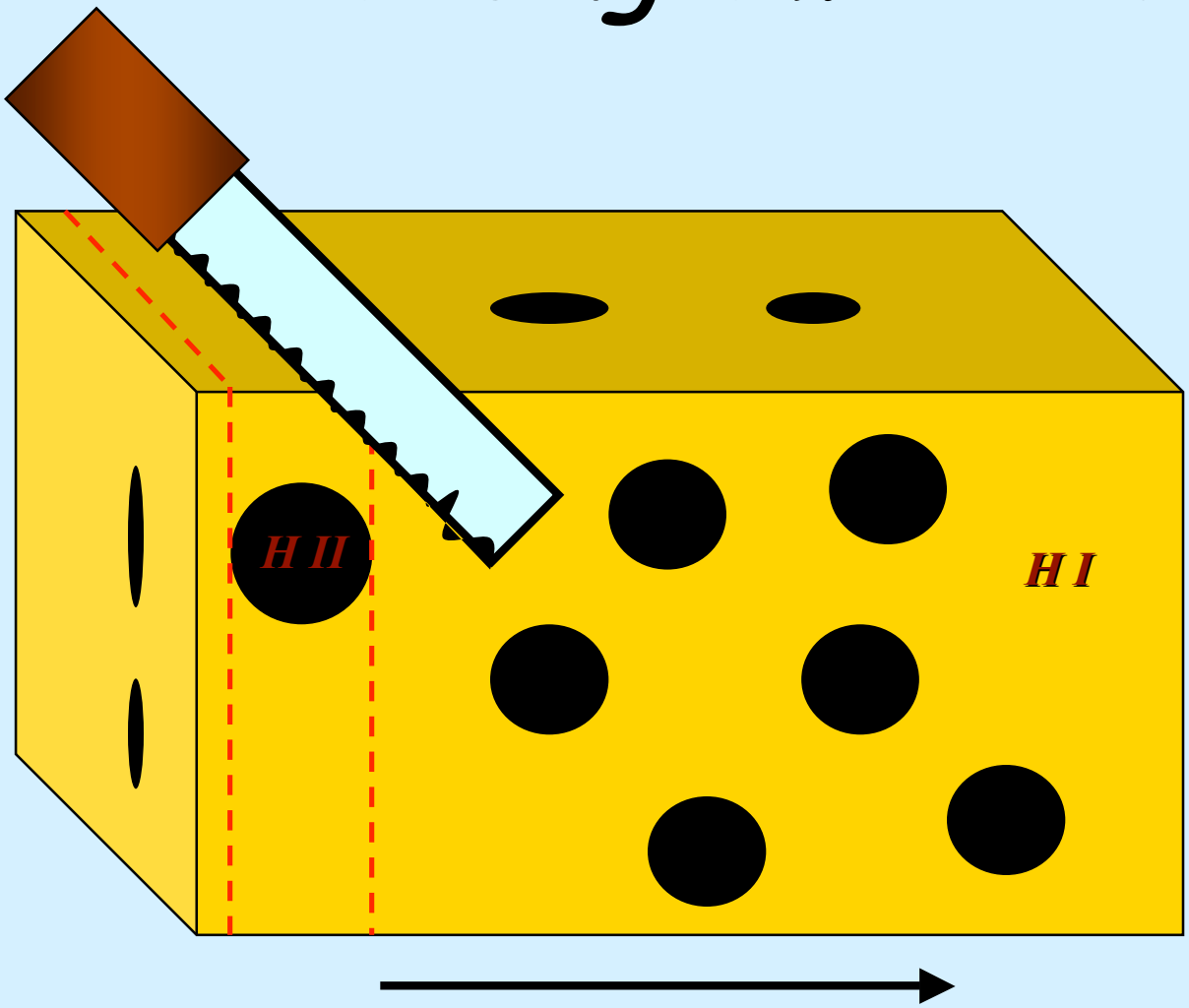
Zaldarriaga, 2003



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

courtesy C. Carilli

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

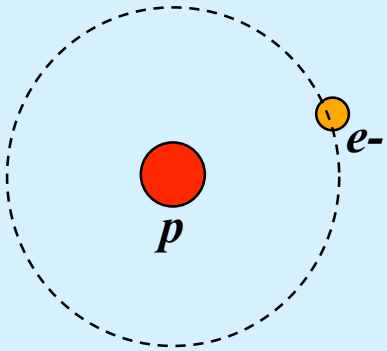


Observed wavelength ⇔ distance

21cm (1+z)

(Loeb, 2006, astro-ph/063360)

Hydrogen



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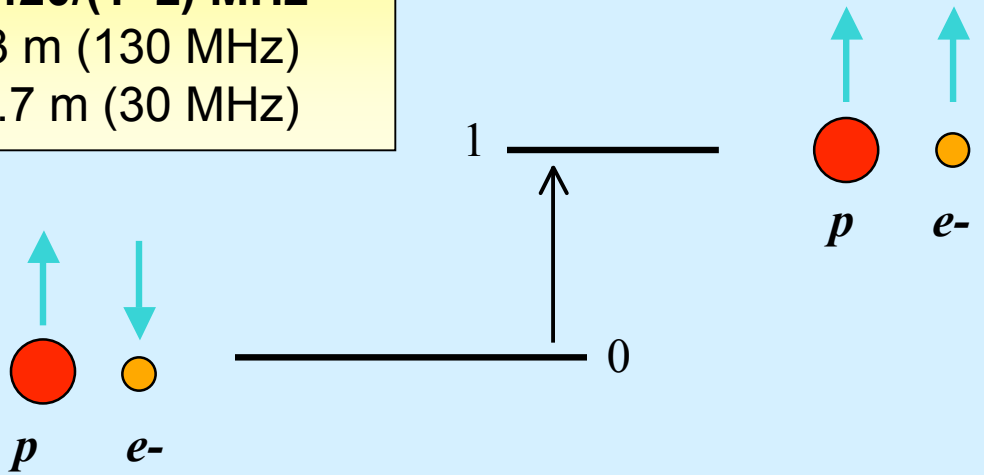

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