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Probing the Dark Ages with 21 cm Absorption

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ABSTRACT

A brief overview of detecting neutral hydrogen gas during the cosmic "Dark Ages" in absorption against the background cosmic microwave background is given. If it could be observed this signal would be more important for cosmology than the cosmic microwave background.

Between the recombination epoch when the cosmic microwave background (CMB) decoupled from matter at $z \sim 1000$ to the appearance of the first sources of light at $z \sim 30$ lies the cosmic "Dark Ages." There is a wealth of cosmological information in this epoch if this era could be probed observationally. Fortunately theory predicts for $200 \gtrsim z \gtrsim 30$ the spin temperature of the neutral hydrogen gas drops below the temperature of the CMB. The hydrogen will absorb CMB radiation at the spin flip transition of 21 cm and appear in absorption against the CMB. This absorption, redshifted to low radio frequencies today, should be observable though in practice it will be very challenging and full 3D imaging may require instruments in very exotic locations.

The ground state of hydrogen is split into hyperfine levels depending on whether the spins of the proton and electron are aligned (state 1, excited) or anti-aligned (state 0). The energy difference of these levels corresponds to a wavelength of 21 cm ($\nu = 1420$ MHz). A spin temperature, T_S, can be defined from the number densities of the level populations:

$$\frac{n_1}{n_0} = 3\exp(-0.068 \text{ K}/T_S)$$

During the Dark Ages the spin temperature is determined by relatively simple processes of absorption and stimulated emission from the CMB and collisions with other gas particles. The time evolution of the density of atoms in the ground state can be written:

$$\frac{dY}{dz} = -\left[H(1+z)\right]^{-1} \times \left[-Y(C_{01} + B_{01}I_\nu) + (1-Y)(C_{10} + A_{10} + B_{10}I_\nu)\right]$$

where $Y = n_0/n_H$, $n_H = n_1 + n_0 \propto (1+z)^3$ is the total hydrogen density, $H \approx H_0\sqrt{\Omega_m}(1+z)^{3/2}$ is the Hubble parameter at high redshifts, Ω_m is the matter density parameter, A's and B's are the Einstein rate coefficients, C's are the collisional rate coefficients, and I_ν is the blackbody intensity in the Rayleigh-Jeans tail of the CMB, $I_\nu = 2k_B T_{CMB}/\lambda^2$ with $\lambda = 21$cm. Using this equation the spin temperature as a function of redshift can be found, see Figure 1.

When $z \gtrsim 200$, Compton scattering of CMB photons off the residual amount of free electrons in the gas leftover from recombination, and collisions between the free electrons and gas particles keep the gas temperature (and hence the spin temperature) coupled to the CMB temperature, $T_{CMB} \propto (1+z)$. The hydrogen will be not visible against the CMB in this regime. The coupling becomes inefficient at $z \sim 200$, the gas temperature decouples from the CMB and the gas begins cooling adiabatically, $T_{gas} \propto (1+z)^2$. Atomic collisions dominate CMB absorption and the spin temperature thermalizes with the gas temperature. Around $z \sim 70$ the decreasing gas density and temperature make collisions inefficient, absorptions dominate and the spin temperature begins returning to thermal equilibrium with the CMB. For $z \lesssim 30$ the spin temperature equalizes with the CMB temperature. The hydrogen would become invisible again but this is about the time when the first collapsed objects form and produce ionizing radiation which complicates the evolution of T_S.

In the window from $30 \lesssim z \lesssim 200$ the cosmic HI should be visible in absorption against the CMB. The brightness temperature of the CMB is given by:

$$T_b = \tau(T_S - T_{CMB})/(1+z)$$

$$\tau = \frac{3c\lambda^2 h A_{10} n_H}{32\pi k_B T_S H(z)}$$

Fluctuations in the hydrogen density produce fluctuations in T_b by altering the optical depth τ and by altering the spin temperature in the fluctuation region. An increase in density raises the collision rate which increases the coupling of T_{gas} to T_S, which lowers T_S. This results in fluctuations of hydrogen absorption on the CMB. These anisotropies should be visible at low radio frequencies (< 50 MHz).

Angular power spectra of anisotropies in the low frequency brightness temperature can be produced analogous to the CMB at mm wavelengths. Figure 2 shows angular power spectra of 21 cm anisotropies at several redshifts. Cosmological parameters can be deduced from the 21 cm power spectra similar to the CMB but with 2 major advantages. The 21 cm observations can probe density fluctuations down to the baryonic Jeans scale, which reaches its minimum value $\sim 3 \times 10^4 M_\odot$ in this redshift range. Photoionization heating during the epoch of reionization raises the baryonic Jeans mass several orders of magnitude which also gives 21 cm observations an advantage over observations of the Ly-α forest. The CMB power spectrum is limited to multipoles $l < 3000$ ($k < 0.2$ Mpc^{-1}) by Silk dampening and the finite size of the surface of last scattering while 21 cm can probe to $l < 10^7$ ($k < 10^3$ Mpc^{-1}). Another advantage the 21 cm spectra have is lower cosmic variance because the dark ages is a volume with many independent modes unlike the single last scattering surface of the CMB. Observations at different frequencies probe independent regions. An observatory that detects the 21 cm signal over a frequency range $\Delta\nu$ centered on ν to a multipole l_{max} measures a total of $N_{21cm} \sim 3 \times 10^{16}(l_{max}/10^6)^3(\Delta\nu/\nu)(z/100)^{-1/2}$ independent samples. In contrast, including both temperature and polarization information for the CMB, $N_{CMB} = 2l_{max}^2 \sim 2 \times 10^7(l_{max}/3000)^2$.

Probing the power spectrum of density perturbations to much lower mass scales with lower cosmic variance would allow 21 cm observations to measure or improve constraints on the conditions at the end of inflation and alternatives to the standard ΛCDM, see Figure 3. Non-Gaussian deviations in the spectrum of perturbations from inflation would be measurable at a level $\sim N_{21cm}^{-1/2}$, easily reaching the expected signal at $\gtrsim 10^{-6}$ (Maldacena 2003). Deviations due to a tilted power spectrum or a running of the spectral index imprinted at the inflation era would be easily visible. Cutoffs in the power spectrum produced by streaming motions if the dark matter is a warm particle that decoupled while relativistic or produced by modifications to the inflation potential (e.g. a discontinuity in the second derivative of the inflation potential, Kamionkowski & Liddle 2000) would be apparent. The amount that neutrinos contribute to the cosmic matter density could also be measured.

Absorption of the CMB at 21 cm ($\nu = 1420$ MHz) in the rest frame of the hydrogen gas will be redshifted to longer wavelengths today: $\lambda = 21 \text{ cm} \times (1+z)$. The redshift range $30 < z < 200$ corresponds to wavelengths $6.5\text{m} < \lambda < 42.2\text{m}$, or frequencies 46 MHz $> \nu >$ 7 MHz. Observing the 21 cm anisotropies at these frequencies will be a major challenge. The sky at these frequencies is contaminated by foreground sources of synchrotron emission from the Galaxy and from extragalactic sources. The sky temperature from regions of minimum emission at high Galactic latitudes is approximately given by:

$$T_{sky} \sim 180 \left(\frac{\nu}{180MHz}\right)^{-2.6} K$$

This gives $\sim 10^4$K at 46 MHz and $\sim 10^6$K at 7 MHz. The expected 21 cm signal is $\sim 10^{-2}$K, requiring foreground subtractions to levels of 10^{-6} to 10^{-8}. One advantage is both Galactic and extragalactic emissions vary smoothly and could be subtracted by differencing observations at 2 closely spaced frequencies. Unfortunately radio frequency interference (RFI), both man-made and natural sources, is not spectrally smooth and harder to get rid of. Another source of problems is the Earth's ionosphere which causes phase distortions in the cosmic signal. Techniques similar to adaptive optics at optical wavelengths may be able to remove these distortions. More severe is that the ionosphere becomes opaque at frequencies $\nu \lesssim 20$ MHz (z > 70). These difficulties could be circumvented by placing a

Dark Ages observatory on the far side of the Moon. Indeed, the lunar farside may be the only feasible site in the Solar System (Lazio 2007).

The Moon has no permanent ionosphere, the far side is shielded from human generated RFI, and during the lunar night the surface is shielded from Solar burst RFI. To produce imaging spectral-line observations of the 21 cm signal, allowing structures to be distinguished as a function of redshift (tomography), at the required sensitivity of $\sim$ 10mK would require a collecting area on the order of 10 km^2 (Furlanetto et al. 2006). The low frequencies for a Dark Ages observatory make an array of simple dipoles the likely design. The dipoles would be collected into stations of $\sim$ 100 dipoles and $\sim$ 1000 stations to provide the necessary collecting area. The expected size of the HI structures are on the order of arcmins, requiring baselines up to 50 km. The bottom of a crater on the lunar farside could provide smooth terrain of sufficient size to locate the stations.

The technical challenges to constructing an array on the far side of the Moon are massive and must be overcome before construction could be undertaken. NASA has awarded grants to 2 teams led by scientists at MIT and the Naval Research Lab to study the concept and develop a detailed plan including a technological road map for a Dark Ages lunar observatory. The construction of such an observatory would not begin earlier than 2025. An observatory capable of fully measuring the signals from 21 cm absorption in the cosmic Dark Ages is firmly set in the future, but the information cannot be obtained in any other way and the potential payoffs for cosmology are immense.

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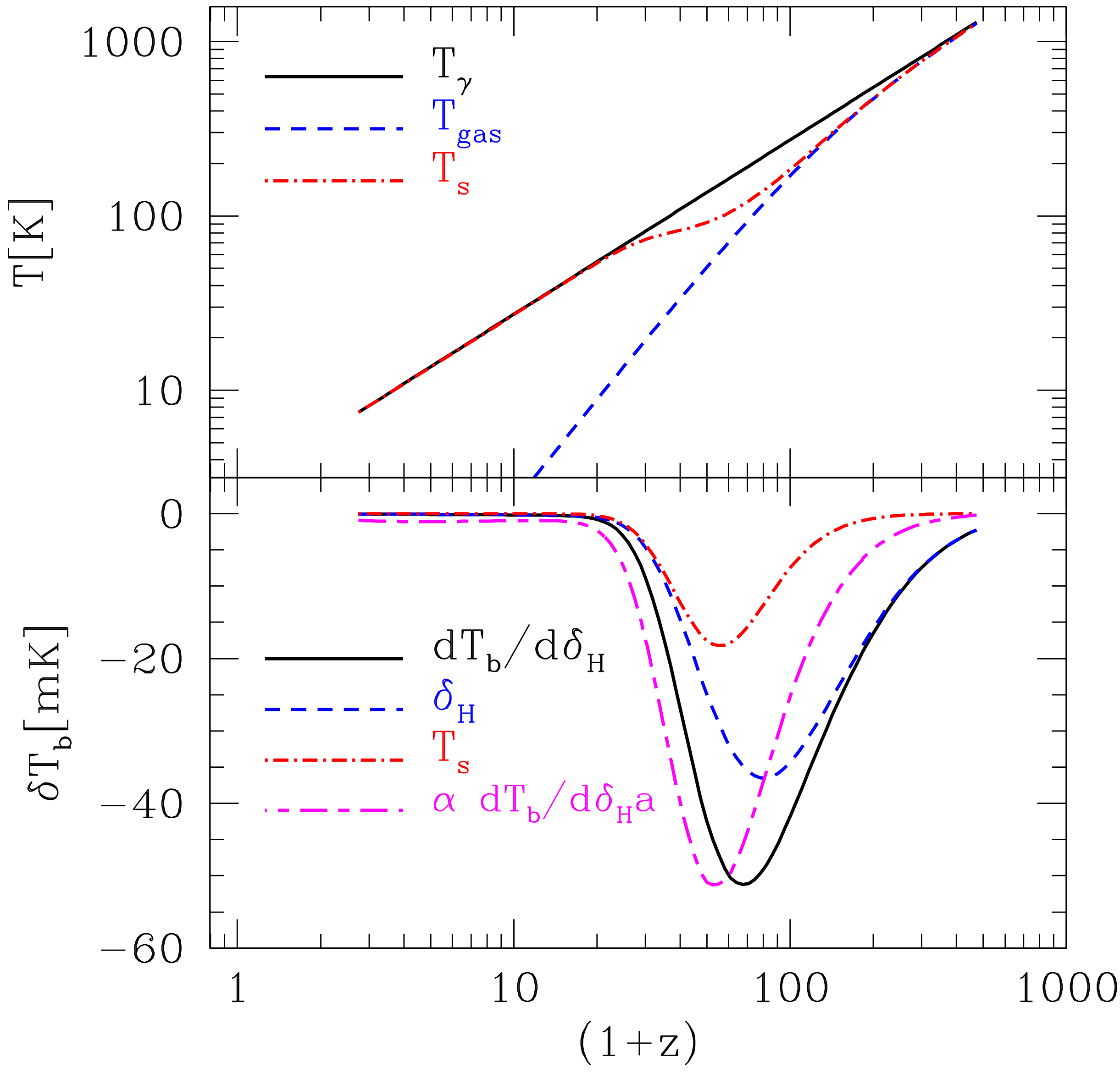

Fig. 1.— From Loeb & Zaldarriaga (2004). *Top:* the evolution of the gas, CMB, and spin temperatures with redshift for a standard ΛCDM cosmology. *Bottom:* The brightness temperature fluctuation δT_b (pink dot-dash-dash). $\delta T_b = (dT_b/d\delta_H)\delta_H$ where δ_H is the overdensity in hydrogen ($\delta_H \propto a$, a =scale factor). $dT_b/d\delta_H$ includes contributions from δ_H and T_S.

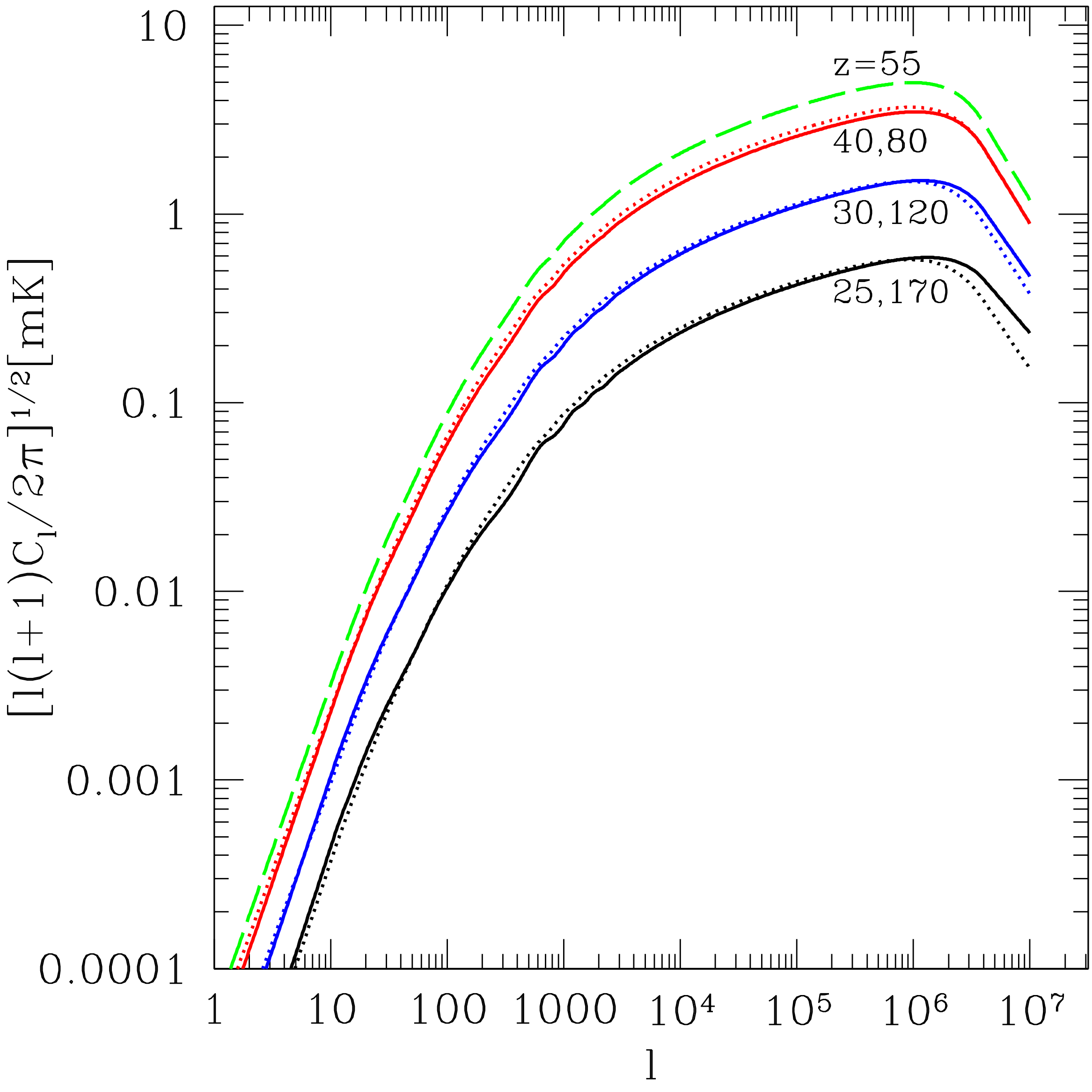

Fig. 2.— From Loeb & Zaldarriaga (2004), angular power spectra of 21 cm anisotropies at various redshifts. The spectra extend to much higher multipoles than the CMB.

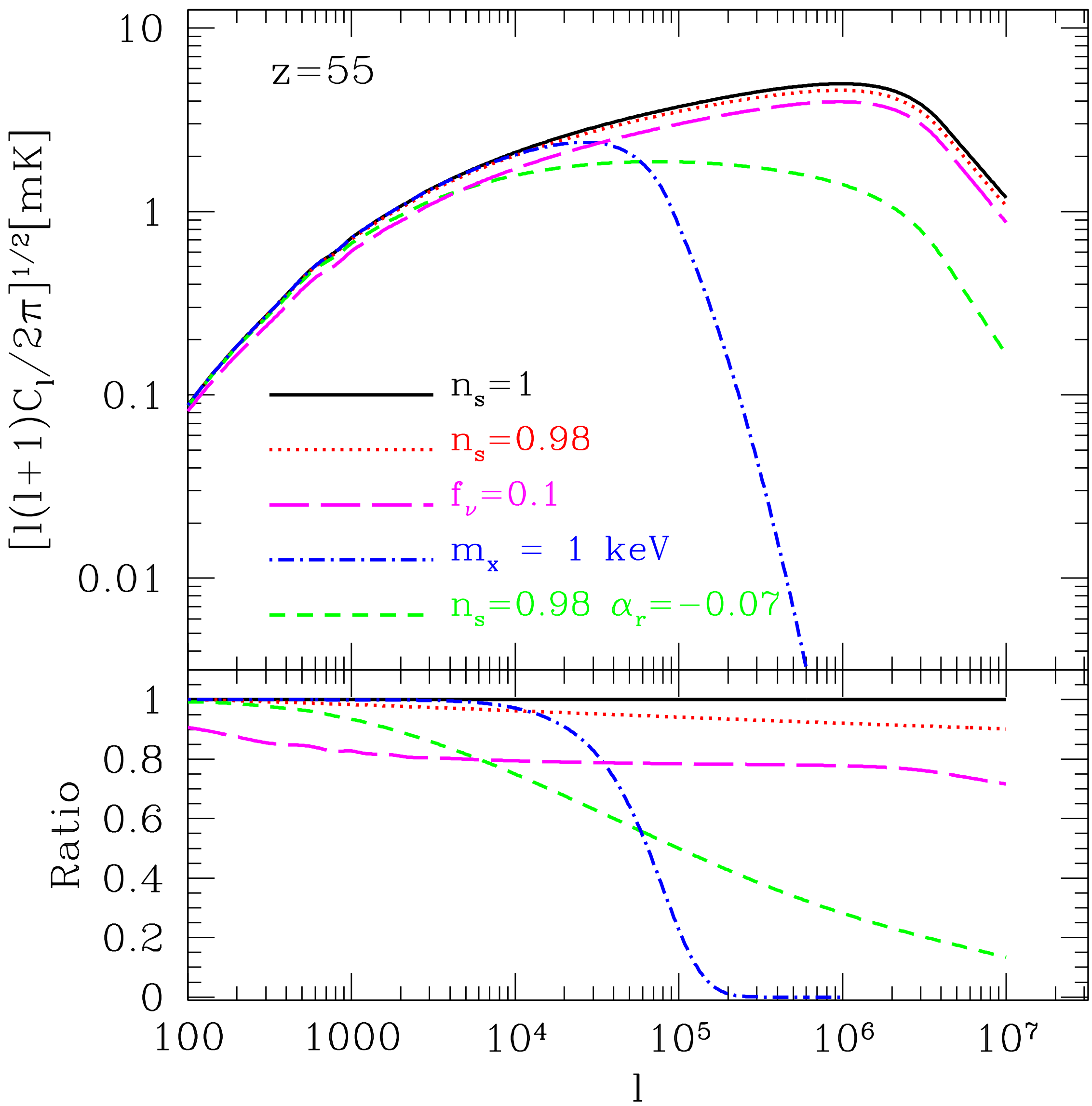

Fig. 3.— From Loeb & Zaldarriaga (2004), the power spectrum of 21 cm anisotropies at z=55 for various cosmologies. Black solid: scale invariant ΛCDM. Red dotted: tilted ΛCDM. Green short-dashed: titled ΛCDM with a running of the spectral index. Blue dot-dashed: warm dark matter with a thermal particle mass of 1 keV. Pink long-dashed: a model with 10% of the matter density in neutrinos. The bottom panel gives the ratio of power spectra against scale invariant ΛCDM