

Predictions for the Sky-Averaged Depth of the 21 cm Absorption Signal at High Redshift in Cosmologies with and without Nonbaryonic Cold Dark Matter

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We consider the 21 cm absorption signal expected at high redshift in cosmologies with and without nonbaryonic cold dark matter. The expansion of the early Universe decelerates strongly with dark matter, but approximately coasts without it. This results in a different path length across the epochs when absorption is expected, with the consequence that the absorption is predicted to be a factor of ~ 2 greater without dark matter than with it. Observation of such a signal would motivate consideration of extended theories of gravity in lieu of dark matter.

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Introduction.—The nature of the missing mass remains one of the great unsolved problems in physics. The existence of nonbaryonic cold dark matter (CDM) is an apparent requirement of modern cosmology for a variety of reasons [1], perhaps most notably [2,3] the cosmic microwave background (CMB). This cosmic dark matter is widely assumed to be a weakly interacting massive particle (WIMP), yet decades of direct detection experiments have so far yielded only null results [4–6]. These nondetections have repeatedly excluded regions of parameter space where positive detections had been expected [7]. More generally, there is no positive experimental evidence for supersymmetry, a necessary prerequisite for the hypothesized WIMPs. Meanwhile, some astronomical data provide reason to doubt the existence of CDM outright [8–10].

This situation motivates consideration of alternatives to WIMP dark matter. Here we consider the possibility that the effects we have been interpreting as dark matter might in fact point to a need for an extended theory of gravity. Such a possibility is observationally well motivated [11,12], with powerful arguments that can be made for and against both the dark matter and extended gravity interpretations [13].

The modified Newtonian dynamics (MOND) hypothesized by Milgrom [14] has had many *a priori* predictions [15] come true [16–23]. This should not happen if dark matter is the correct interpretation of the observed discrepancies. However, while MOND has the interesting property that dynamics [24] become scale invariant [25], attempts to incorporate it into a generally covariant framework have been frustrating. The most prominent example of such a theory, TeVeS [26], fails to fit the CMB [27], grow structure [28], or be consistent with observations of gravitational waves [29].

The failure of the specific theory TeVeS does not falsify the more general hypothesis of scale invariant dynamics [30],

but we are left without a clear theory for cosmology in this context. Fortunately, the physics of the 21 cm absorption is straightforward, depending only on atomic physics and the fact that the Universe is expanding. This provides the opportunity to outline some very general expectations. Generically, we expect a universe devoid of nonbaryonic dark matter (NoCDM) to be low density, and thus experience less deceleration at early times [31] than the conventional Λ CDM [32] Universe. As a consequence, there is a greater path length to the surface of last scattering that leads to a stronger absorption signal.

21 cm absorption in the early Universe.—The early ($10 \lesssim z \lesssim 1000$) Universe contains an enormous amount of information [33], but remains largely unexplored. These epochs follow recombination but precede the bulk of star formation, so the baryonic content is expected to be a largely neutral gas composed of hydrogen and helium in their primordial 3:1 mass ratio [34,35]. During this time [36], we expect an absorption signal from the 21 cm spin-flip transition of neutral hydrogen [37] seen against the backdrop provided by the CMB from $z = 1090$ [3].

The relevant atomic physics is straightforward yet remarkably rich. We are concerned with three distinct temperatures: that of the radiation field T_γ , the kinetic temperature of the gas T_k , and the spin temperature of the 21 cm line T_S that specifies the occupation of the hyperfine levels [37]. The expansion of the Universe leads to a divergence between the kinetic temperature of the gas, which varies approximately as $(1+z)^2$, and that of the radiation field, which varies as $(1+z)$. The spin temperature is bounded between the two, $T_k \leq T_S \leq T_\gamma$, and specified by [37]

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_i T_k^{-1}}{1 + x_i}. \quad (1)$$

Here, x_i generically represents any physical effect that couples the spin temperature to the gas. We expect absorption whenever $T_S < T_\gamma$.

There are two distinct physical processes at work at different points in the early Universe. Consequently, we expect to see 21 cm absorption against the microwave background at two distinct epochs, “cosmic dawn” ($z \approx 20$) and the “dark ages” ($z \approx 100$). During the dark ages, the dominant coupling x_i is collisional. At cosmic dawn, the dominant mechanism is the Wouthuysen-Field effect [38,39] stemming from the resonant scattering of Ly α photons produced by the first stars.

To compute the spin temperature during the dark ages, we utilize existing fitting functions for x_i : see Eq. (10) of Ref. [37] and the subsequent text. As the Universe expands, the spin temperature begins to diverge from the radiation temperature after decoupling, tending towards the cooler gas temperature. This leads to the expectation of an absorption signal that is maximized around $z \approx 100$, after which the spin temperature reverts to the radiation temperature as collisions become rare in the expanding Universe. This is straightforward atomic physics driven by H-H and e-H scattering, so provides an especially clean test.

As collisions decline, the Wouthuysen-Field effect begins to dominate the coupling. This is driven by the appearance of the first stars that produce Ly α photons. Resonant coupling with these Ly α photons plays the same role as collisions during the dark ages. The spin temperature again diverges from the radiation temperature, approaches the gas temperature, then rebounds, giving the expectation of another redshift dependent absorption trough [37].

Proper estimation of the Wouthuysen-Field effect depends on the spectrum of the first stars, and thus requires the construction of a model for these first sources of radiation [37,40,41]. Such models are, of necessity, rather uncertain, though we note that in most plausible models, the coupling is efficient thanks to the high optical depth of Ly α photons so that the spin temperature very nearly reaches the gas temperature [42]. The maximum possible absorption signal occurs in the limit $T_S \rightarrow T_k$, so rather than build a specific model, we take the general case that gives the maximum possible absorption signal. This follows simply by setting $T_S = T_k$ at the redshifts of interest ($16 \leq z \leq 19$). The actual signal might be a bit less, but it certainly should not be more in a given cosmology.

Quantitatively, the amplitude [40,43] of the 21 cm brightness temperature T_{21} as a function of redshift z is given by

$$T_{21}(z) = T_0 \frac{x_{\text{HI}}}{\mathfrak{h}_z} \left[(1+z) f_b \left(\frac{\omega_b}{0.02} \right) \right]^{1/2} \left(1 - \frac{T_\gamma}{T_S} \right). \quad (2)$$

Here, $T_0 = 20$ mK, x_{HI} is the neutral hydrogen fraction (very nearly unity over the relevant range of redshifts), \mathfrak{h}_z is a factor for the cosmology-specific expansion history

defined below, $f_b = \Omega_b / (\Omega_b + \Omega_{\text{CDM}})$ is the cosmic baryon fraction, and $\omega_b = \Omega_b h^2$ [44] is the baryon density. Three basic elements impact the optical depth of the 21 cm line seen in redshifted absorption towards the CMB: the temperature evolution of the Universe, the density of hydrogen atoms, and the path length along which the absorption occurs.

The evolution of the radiation temperature is simply $T_\gamma = (2.725\text{K})(1+z)$. The evolution of the gas temperature requires numerical solution of the Saha equation in an expanding universe, which we accomplish with the industry-standard code RECFAST [45,46], including all updates to the atomic physics [47,48]. RECFAST also provides the neutral fraction of hydrogen; the cosmologies considered here have a very similar temperature history and $x_{\text{HI}}(z)$.

Cosmological models.—To illustrate the expected difference between a universe with and without nonbaryonic dark matter, we compute the temperature evolution and corresponding 21 cm absorption signal for two cosmologies: Λ CDM and NoCDM ($\Omega_{\text{CDM}} = 0$). We adopt for Λ CDM parameters from Planck [3] for input to RECFAST as noted in Table I. For Eq. (2), the relevant quantities are $\omega_b = 0.022$ and $f_b = 0.156$. These parameters are now so tightly constrained that the absorption signal from the dark ages must follow with little uncertainty, and that at cosmic dawn is strongly bounded.

For specificity, we adopt the NoCDM model from the last row of Table III in Ref. [49]. However, most of the parameters explored in detail there are irrelevant here. We have calculated variations on the NoCDM model; the results presented here hold generically provided that $\omega_b \approx 0.02$ and $\Omega_{\text{CDM}} = 0$, irrespective of other cosmological parameters [50].

The great success of NoCDM is that it correctly predicted [51] the amplitude of the second peak [52] in the acoustic power spectrum of the CMB, and was the only model to do so *a priori*. The chief failing of NoCDM is that

TABLE I. Predicted spin temperatures and 21 cm absorption.

z	ν (MHz)	T_γ (K)	Λ CDM ^a NoCDM ^b		Λ CDM NoCDM	
			T_S (K)		T_{21} (mK)	
Cosmic dawn						
16	83	46.3	6.16	6.56	−226	−499
17	79	49.1	6.90	7.34	−218	−482
18	75	51.8	7.67	8.15	−211	−467
19	71	54.5	8.48	9.02	−204	−452
Dark ages						
50	28	139	119	119	−10	−22
100	14	275	197	203	−33	−68
200	7	548	471	478	−19	−37

^a Λ CDM: $\Omega_b = 0.0488$, $\Omega_{\text{CDM}} = 0.2633$, $\Omega_\Lambda = 0.6879$, $h = 0.675$.

^bNoCDM: $\Omega_b = 0.039$, $\Omega_{\text{CDM}} = 0$, $\Omega_\Lambda = 0.91$, $h = 0.75$ (RECFAST inputs).

it underpredicts the amplitude of the third and subsequent peaks [53]. Despite preceding the Planck satellite by a decade, the specific model of Ref. [49] utilized here provides an excellent fit [13] to the Planck data with $\ell < 600$ with zero adjustment. However, it provides no fit nor explanation for the data at $\ell > 600$, and we are left to imagine that some feature of a more general theory might account for this aspect of the data. The forcing term we currently attribute to CDM might instead be caused, e.g., by a scalar field [27], but I am not aware of an extended theory of gravity that provides a detailed fit to the acoustic power spectrum in the same sense that Λ CDM does.

For our purposes here, NoCDM is merely a proxy for the unknown unknowns. The important difference from Λ CDM is the baryon fraction, $f_b = 1$. We adopt $\omega_b = 0.022$ to be identical with Λ CDM so that the baryon fraction is the main difference in Eq. (2). Notably, to maintain $\Omega_b = 0.039$ as used in Ref. [49] implies $h = 0.75$: the Hubble constant is thus not in tension with local measurements [54,55].

The way Eq. (2) is written subsumes the expansion history of the Universe. This is critical, as the path length for absorption depends on the variation of the Hubble parameter, $H(z)$. Equation (2) has been derived [40] using the approximation

$$\tilde{H}(z) = H_0 \Omega_m^{1/2} (1+z)^{3/2}. \quad (3)$$

This suffices for Λ CDM but is inadequate for NoCDM, so we compute for both the full expression

$$H^2(z) = H_0^2 [\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 - \Omega_k(1+z)^2], \quad (4)$$

where Ω_r is the radiation density, including neutrinos. This is not entirely negligible in NoCDM at the higher redshifts of interest here. Together, Eqs. (3) and (4) provide the correction factor $\mathfrak{h}_z = H(z)/\tilde{H}(z)$. It is at most a few percent for Λ CDM. For NoCDM, it is 5% at cosmic dawn, and $\sim 10\%$ during the dark ages ($z \approx 100$). While the specific NoCDM model we adopt provides the run of \mathfrak{h}_z necessary for the calculation here, more generally the absorption signals provide an empirical constraint on the expansion history $H(z)$ [56–58] in a huge but otherwise inaccessible volume of the Universe. A significant deviation from the predictions of both Λ CDM and our simple NoCDM model would be a strong hint that the expansion history of the Universe is incompatible with standard cosmology.

Results.—The main difference in Eq. (2) between the cosmologies considered here is the baryon fraction: $f_b = 0.156$ in Λ CDM and $f_b = 1$ in NoCDM. This leads to a difference in absorption signal, as illustrated in Table I and Fig. 1. One expects roughly twice as much absorption in NoCDM as in Λ CDM.

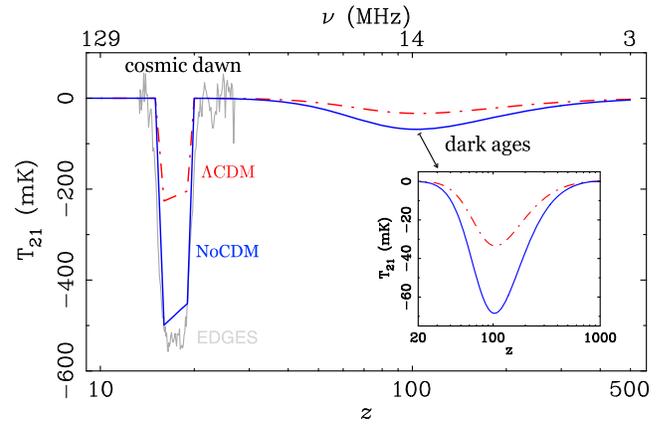


FIG. 1. The sky-averaged 21 cm absorption as a function of redshift, with the corresponding frequency noted at top. The prediction for Λ CDM with Planck parameters [3] is shown as the broken red line; a model (NoCDM [49]) without cold dark matter is shown as the solid blue line. The inset magnifies the absorption during the dark ages, which is expected to be weaker than that at cosmic dawn. The dark ages provide a cleaner test, as the signal at cosmic dawn depends on the spectrum produced by the first stars. We ignore these astrophysical details here to show the maximum possible signal by simply setting $T_s = T_g$ for $16 \leq z \leq 19$. This redshift range is motivated by the detection reported by EGDES [59], shown in gray.

Physically, the reason for the greater optical depth in NoCDM is a greater path length to the surface of last scattering, not an increase in the density of hydrogen. The key factor encoded in f_b in Eq. (2) is the difference in mass density Ω_m in Eq. (3). A universe with a large mass density like Λ CDM decelerates strongly at the high redshifts considered here before accelerating at late times. A low density universe devoid of nonbaryonic dark matter is close to the coasting limit. This leads to a longer path length and correspondingly greater optical depth.

We must at this juncture bear in mind that NoCDM is merely a proxy for some unknown, underlying theory. This could be quite different, though hopefully distinct from Λ CDM. However, the near-coasting limit seems appropriate for a very simple physical reason. Without dark matter, there is not much mass for gravity to operate on, even if the force law is modified. Consequently, the near-coasting approximation should generically be a good one, as it is in the specific case of MOND [31,60].

The expected absorption at cosmic dawn has recently been detected by EDGES [59]. This is shown in Fig. 1 along with the model predictions. The depth of the observed absorption is consistent with NoCDM, within the formal uncertainties. The possible absorption ranges over $451 < |T_{21}| < 499$ mK compared to the observed 500^{+500}_{-200} mK at 99% C.L. [59]. The predicted range is for the maximum possible absorption, which we expect to be very nearly realized in practice [42].

In contrast, Λ CDM is not consistent with EDGES [59,61,62]. For Planck parameters, the maximum possible absorption is 226 mK at $z = 16$ (Table I). This is significantly less than the 99% C.L. of $|T_{21}| > 300$ mK [59].

Preserving Λ CDM requires some form of special pleading. Examination of Eq. (2) shows that a signal of arbitrary strength may be obtained by adjusting the ratio T_γ/T_S . These are set by cosmology and atomic physics, so are not easily altered. Nevertheless, the necessary effect might be obtained by increasing T_γ with some hypothetical radio sources at very high redshift [63,64], or by decreasing T_S with some nonstandard physics [65–68]. These are unnatural auxiliary hypotheses of the sort that can always be invoked to save the phenomena. In contrast, the observed signal is entirely natural in a universe devoid of CDM [43,69].

The EDGES [59] result is the first detection of the expected absorption, and may be subject to a variety of systematic errors. While we have no reason to doubt its veracity, it is a challenging observation that requires subtraction of strong foreground signals. Given the importance of the result, we hope to see it independently checked by other experiments.

So far, we have considered only the magnitude of the absorption. There is further information in its timing and shape. Given the tentative nature of the detection, we caution against over-interpreting these features. For completeness, we note that the early occurrence of cosmic dawn is natural in MOND [60], though it may also be obtained in Λ CDM [70] depending on the nature of the first sources (see [49] and references therein). The shape of the signal is entirely unexpected, being much sharper than anticipated [71]. The simple “on-off” model adopted here provides a surprisingly good match to the observed redshift dependence without attempting to do so. This might be suggestive of the sudden onset of structure formation anticipated in MOND [60].

Further predictions.—Dark ages: The EDGES [59] detection at cosmic dawn opens a new window on the early Universe. At still higher redshift, the dark ages remain to be probed. The prediction of NoCDM is that the amplitude of absorption will again be about twice that expected in Λ CDM with Planck [3] parameters (Table I). This is in principle a clean test, because simple atomic scattering dominates the coupling of T_S to T_k . Both are readily calculable, and depend only on atomic physics and the fact that the Universe is expanding.

In order to observe the signal at $z \approx 100$ requires very low frequency data, below Earth’s ionospheric cutoff ($\nu < 30$ MHz). Such data would be best obtained from the far side of the moon, using the moon to shade the instrument from terrestrial radio interference. These results add motivation for such an experiment [72]. Detecting the 21 cm signal from the dark ages is already compelling motivation, but it additionally enables a fundamental test of these differing cosmological hypotheses.

Structure formation: The discussion above is as generic as possible, seeking only a test of whether the Universe contains CDM (see also Refs. [9,73]). The approach here suffices to consider the sky-averaged 21 cm absorption intensity. However, we also anticipate fluctuations in this intensity along different lines of sight [37]. I discuss here some basic expectations for the power spectrum of these fluctuations.

Following the MOND cosmogony outlined by Sanders [60], no growth can occur prior to decoupling from the radiation field at $z \sim 200$. Once the radiation loses its grip, density fluctuations find themselves deep in the low acceleration regime. Consequently, the MOND effect is large, and they behave as if there were lots of dark matter: structure formation proceeds rapidly [74–77]. The Sanders cosmogony anticipates large galaxies forming at $z \approx 10$, clusters of galaxies at $z \approx 3$, and the emergence of the cosmic web at $z \sim 5$. In contrast, contemporaneous Λ CDM models predicted very little structure at these times, with only 1% of stars forming at $z > 5$ [78]. The early onset of star formation [79], the “impossibly early galaxy problem” [80], the presence of clusters of galaxies in the early Universe [81–84], and the strong clustering of quasars at high redshift [85] were all anticipated long before their observation by the Sanders cosmogony [60].

MOND is nonlinear, so quantitative prediction of the power spectrum [74] is beyond the scope of this Letter. Nonetheless, we can anticipate the amount of power relative to the linear growth of perturbations in Λ CDM. Early on, $z \approx 200$, we expect there to be less power than in Λ CDM due to Silk damping. By $z \approx 30$, this situation will have reversed, with structures forming rapidly over a large range of mass scales, yielding more fluctuation than expected in Λ CDM.

The rapid development of structure at high redshift anticipated in the Sanders cosmogony [60,75] leads to the expectation that the formation of the first stars is more sudden and widespread than expected in Λ CDM [49]. This leads to early reionization: the optical depth to the surface of last scattering is $\tau \approx 0.17$ in Ref. [49]. The sudden onset of cosmic dawn is qualitatively consistent with the shape of the EDGES absorption trough (Fig. 1).

Another expectation for the power spectrum at high redshift is the presence of pronounced baryonic features [28,69]. These do not necessarily persist to low redshift because mode mixing is likely in the nonlinear structure formation driven by MOND. However, the power spectrum that first emerges after decoupling should preserve the imprint of strong baryonic oscillations [69]. This is best tested during the dark ages at the highest accessible redshift.

Neutrino mass: The range of allowed neutrino mass in Λ CDM is strictly limited by neutrino oscillations [86] and the latest Planck results [87] to fall in the narrow range $0.06 < \sum m_\nu < 0.12$ eV. Though not relevant to 21 cm

absorption, there are indications of a larger neutrino mass ($m_\nu > 0.5$ eV) in the models considered by Ref. [49]. This provides another test to distinguish between Λ CDM and NoCDM. An experimental determination that $\sum m_\nu > 0.12$ eV would falsify Λ CDM. The same limit does not apply in MOND, for which $m_\nu \sim 1$ eV might help prevent it from overproducing structure [76] and explain the excess discrepancy in clusters of galaxies [88].

Conclusions.—A challenge for modern cosmological theory is to identify definitive predictions by which Λ CDM would be subject to falsification [9,73]. Previous attempts [51] with the CMB succeeded [49,52] before failing [13] due to previously unacceptable degrees of freedom [89]. I worry that the current picture allows so much room for auxiliary hypotheses that there is no possibility of discerning that it is incorrect, should that happen to be the case.

Here I have highlighted the amplitude of the 21 cm absorption as a possible test. Generically, I predict that a universe devoid of CDM will exhibit about twice as much absorption as is possible in Λ CDM. Taken at face value, the EDGES [59] detection is in serious conflict with Λ CDM [61] while corroborating the NoCDM calculation made here. The various auxiliary hypotheses [62] that have been offered to reconcile the EDGES signal with Λ CDM highlight my concern for its falsifiability.

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