New light on 21cm intensity fluctuations from the dark ages

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After cosmological recombination, before reionization, the universe is 99.97% neutral.

Neutral hydrogen is observable in spin-flip hyperfine transition at 21cm / 1420 MHz

Observable: brightness temperature

\[ T_b = T_{\text{line}} - T_{\text{cmb}} = \tau (T_s - T_{\text{cmb}}) \]

\[ \frac{n_1}{3n_0} = e^{-E_{10}/T_s} \]

\( T_s \) determined by balance between collisions, radiative transitions [and Ly\( \alpha \) scattering at low z]
21cm cosmology basics

- Average $T_b(z) \rightarrow \text{history}$ of the early universe

- Fluctuations $\delta T_b(x, z)$ or $\delta T_b(k, z) \rightarrow \text{geography}$ of the universe: $P(k), B(k_1,k_2,k_3)$
21cm fluctuations during the dark ages: a new scale frontier

CMB: $k \lesssim k_{\text{Silk}} \sim 0.15 \text{ Mpc}^{-1}$
LSS: $k \lesssim k_{\text{NL}} \sim \text{few } 0.1 \text{ Mpc}^{-1}$

21cm: $k \lesssim k_{\text{Jeans}} \sim 300 \text{ Mpc}^{-1}$

3D power spectrum

- $n_s$, running
- Warm dark matter
- Massive neutrinos
- Non-gaussianity
- $P(k \sim 300 \text{ Mpc}^{-1})$

Loeb & Zaldarriaga 2004

Tegmark & Zaldarriaga 2009
A very challenging observation

- **Earth ionosphere** becomes opaque at $v \approx 10$ MHz ($z \approx 140$)
- **Foreground emission** steeply rises at low frequencies

At $z = 50$, $\lambda = 10$ m.
Array size $\approx 1$ km ($\ell/100$)

Measuring anisotropies on angular scales $\ell \approx 10^4$-$10^5$ ($k \approx 1$-$10$ Mpc$^{-1}$) will be extremely challenging.
We recomputed the signal accounting for the relative velocity of baryons and CDM (Tseliakhovich & Hirata 2010)

- decrease of small-scale fluctuations
- enhancement of large-scale fluctuations, dependent on the power at $k \sim 300 \, \text{Mpc}^{-1}$

→ Large scale signal gives a handle on very small-scale physics
The relative velocity effect

Tseliakhovich & Hirata 2010

\[ V_{bc} = V_{\text{baryon}} - V_{\text{CDM}} \]

\[ \langle v_{bc}^2 \rangle^{1/2} \approx 30 \text{ km/s} \]

at \( z = 1000 \)

Maximum fluctuations for \( k \sim 0.01 - 0.3 \text{ Mpc}^{-1} \)

(well measured scales)
Effect of a local relative streaming

- Scale of suppression: \[ k_{v_{bc}} \sim \frac{aH}{v_{bc}} \approx 40 \text{ Mpc}^{-1} \]

- The effect is fundamentally non-linear:

\[
0 = \ddot{\delta} + \vec{\nabla} \cdot \vec{v} + \vec{v} \cdot \nabla \delta \\
0 = \dot{\vec{v}} + \vec{\nabla} \phi + (\vec{v} \cdot \vec{\nabla}) \vec{v}
\]
Small-scale baryon power spectrum is a function of the local $v_{bc}$: $P(k \gtrsim 40; v_{bc}) < P(k \gtrsim 40; v_{bc} = 0)$
the local relative velocity. In both cases the relative velocity speeds up the convergence towards the adiabatic limit up to corrections of relative order $i$, i.e. at small scales we only need to account for the linear fluctuations of baryon density (solid lines). Accounting for relative velocity modulates on large scales: the quadratic term does become important and can be neglected for temperature fluctuations, which are driven towards the adiabatic regime for temperature fluctuations, which are driven towards the adiabatic regime earlier on when relative velocities are present.

If we consider the small-scale fluctuations of baryon density, we may first smooth it over an intermediate scale $(l_s = 0.01 \times D_H z)$ before re-averaging over a larger scale $L_s$. This is illustrated in Fig. 7. The enhancement is more pronounced for very small scales. In the absence of relative velocities, the characteristic change in the small-scale baryon overdensity power spectrum is much more pronounced for very small scales. However, resonant excitations leads to a suppression of power around $(k L_s)^2 = 10^{-5}$ at redshifts 100 and 50. The dotted lines illustrate that the long-wavelength modulation of the power spectrum is more pronounced at smaller scales due to resonant excitations.

The first inequality ensures that the long-wavelength smoothing scale is of a few tenths of Mpc, such that the smoothing scale of wavenumber, and at redshifts 100 and 50. The dotted line illustrates that the long-wavelength modulation of the power spectrum is much more pronounced for very small scales. In the absence of relative velocities, the characteristic change in the small-scale baryon overdensity power spectrum is much more pronounced for very small scales.
Effect on the large-scale signal

\( \delta \) is linear in initial conditions

BUT

\( T_b \) is a fully non-linear function of \( \delta \)

\[
\delta T_b = T_1 \delta + T_2 \delta^2 + \ldots
\]
for $z \lesssim 100$, $\delta_s^2 \sim \delta_l$
Enhanced large-scale 21cm fluctuations

![Graph showing the variance of fluctuations per logarithmic scale](image)

- **monopole (z=30)**
- **monopole (z=120)**
- \(\delta T_b^\Pi(k)(z=30)\)
- \(\delta T_b^\Pi(k)(z=120)\)

The graph illustrates the variance of fluctuations per logarithmic scale as a function of wave number \(k\). The different lines represent various scenarios and parameters, demonstrating the large-scale 21cm fluctuations and their enhancements at different redshifts. The graph provides insights into the impact of non-linear terms on the 21cm fluctuations.
Enhanced large-scale 21cm fluctuations

\[ \frac{\delta \Delta_{21}^2}{\Delta_{21}^2} \]

\( k \) [Mpc\(^{-1}\)]

- \( z = 30 \)
- \( z = 120 \)
- \( z = 80 \)
- \( z = 60 \)
Conclusions

We recomputed the dark ages 21cm signal accounting for the relative velocity of baryons and CDM.

For effect of $v_{bc}$ after the first stars form, see Barkana, Fialkov, Visbal et al. 2011-2013

- decrease of small-scale fluctuations
- enhancement of large-scale fluctuations, dependent on the power at $k \sim 300 \text{ Mpc}^{-1}$

Upcoming: quantitative analysis of S/N for various small-scale power spectra/physics
Enhanced large-scale 21cm fluctuations

\begin{align*}
\Delta c_t / c_t &= \Delta v \times \frac{\ell}{H_0} \\
\ell &= 10^3 \times (\Delta v / H_0)^{-1}
\end{align*}