21cm line signals from minihalos as a probe of primordial fluctuations

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Plan of talk

• Introduction: minihalos in dark ages and its redshifted 21 cm line signal

• Application: a probe of primordial fluctuations
  ▶ Spectral runnings of power spectrum
  ▶ Primordial non-Gaussianity

• Summary

Refs:
Introduction

Dark ages (~cosmic dawn)

✓ neutral hydrogen
→ redshifted 21cm line
- tracer of matter fluctuations
- tomography → 3D mapping

Mao+ 2008
Redshifted 21cm line surveys

On-going:

- LOFAR, MWA, PAPER, …

Near future:

- Square Kilometer Array (SKA)
  21cm line from 3<z<27; SKA1-low will start from 2021

- Hydrogen Epoch Reionization Array (HERA)
  main target: 21cm line from 7<z<12

➡ Implications for cosmology and particle physics?
Sources of 21cm line

- Smooth IGM: Iliev+ (2002); Furlanetto & Loeb (2002)
- Minihalos: Many many studies…

$\delta_b$
Minihalos

Halos too small to host galaxies

• No star formation: $T_{\text{gas}} < 10^4 \text{K}$ (inefficient radiative cooling)
  → dense neutral hydrogen inside; resistant to ionization

• Mass: $10^4 M_{\odot} < M < 10^8 M_{\odot}$

Sensitive to small-scale ($<0.1 \text{Mpc}$) fluctuations

• Abundant, even at high-$z$
Minihalos vs IGM

Minihalo contribution can dominate at a broad range of redshifts

Model of IGM consistent with the recent Planck constraint
Adam+1605:03507
Redshifted 21cm line fluctuations from minihalos

\[ \delta[\Delta T_b](\hat{n}, \nu) = \int_{M_{\text{min}}}^{M_{\text{max}}} dM \Delta T_b(M, z_\nu) \frac{dN(M, z_\nu)}{dM} b(M, z) \delta(\vec{r} = r_\nu \hat{n}, z_\nu) \]

frequency ↔ redshift ↔ radial distance

\[ \nu = \frac{\nu_0}{1 + z_\nu} \quad r_\nu = r(z_\nu) \]

strength of 21cm line emission/absorption from single minihalo

mass function

halo bias

sensitive to small-scale (<Mpc) matter fluctuations

matter fluctuations at large scales (>Mpc)

Tomographic angular power spectrum

\[ C_l(z, z') = \frac{1}{2l + 1} \sum_m a_{lm}(z) a_{lm}^*(z') \]

TS, Takahashi, Tashiro & Yokoyama [arXiv:1705.00405]
Tomographic angular power spectrum

* Redshift space distortion is included
Application (1): Primordial spectral runnings

Spectrum of primordial fluctuations

\[ \mathcal{P}(k) \propto k^{n_s - 1 + \frac{1}{2} \alpha_s \ln(k/k^*_s) + \frac{1}{6} \beta_s \ln^2(k/k^*_s) + \ldots} \]

- Many models degenerate in the $n_s$-$r$ plane
- However, they can be distinguished from the scale dependence of $n_s$

Spectral runnings: a key observable for discriminating inflation models
Application (1): Primordial spectral runnings (cont’d)

Parameter response

- Lower order spectral parameters (e.g. $n_s$ or $\alpha_s$) → spectral shapes
- Higher order parameters (e.g. $\beta_s$) → overall amplitudes
  → Solves parameter degeneracy
- Radial scale-dependence also enhances the discrimination
Application (1): Primordial spectral runnings (cont’d)

Forecasted constraints

Combination of CMB and 21cm is beneficial due to lever-arm effect.

\[ \Delta \alpha_s = 10^{-3}, \Delta \beta_s = 10^{-4} \]

Constraints are dependent on \( z_{\text{min}} \) only mildly.

<table>
<thead>
<tr>
<th>( z_{\text{min}} )</th>
<th>10(^{-3})( \Delta n_s )</th>
<th>10(^{-3})( \Delta \alpha_s )</th>
<th>10(^{-3})( \Delta \beta_s )</th>
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<tbody>
<tr>
<td>Planck+SKA</td>
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<td>4</td>
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<td>1.4</td>
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<td>8</td>
<td>2.3</td>
<td>3.0</td>
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<tr>
<td>10</td>
<td>3.6</td>
<td>4.7</td>
<td>1.2</td>
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<tr>
<td>COrE+FFTT</td>
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<tr>
<td>4</td>
<td>0.85</td>
<td>0.96</td>
<td>0.24</td>
</tr>
<tr>
<td>6</td>
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<td>8</td>
<td>1.0</td>
<td>1.2</td>
<td>0.31</td>
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<tr>
<td>10</td>
<td>1.1</td>
<td>1.3</td>
<td>0.33</td>
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</table>
Application (2): Primordial non-Gaussianity

Local type non-Gaussianity:

\[ \Phi(\vec{x}) = \Phi_G(\vec{x}) + f_{NL}(\Phi_G(\vec{x})^2 - \langle \Phi_G \rangle^2) + g_{NL} \Phi_G(\vec{x})^3 \]

- Small in single field inflation: \( f_{NL} \sim O(0.01) \), \( g_{NL} < O(10^{-3}) \)
- Large in multi-field models (e.g. curvaton, modulated reheating, etc.)

Current tightest bound (Planck 2015)

\[ f_{NL} = 0.8 \pm 5.0, \quad g_{NL} = (9.0 \pm 7.7) \times 10^4 \]
Application (2): Primordial non-Gaussianity (cont’d)

Effects on minihalo spectrum

• Coupling between large and small scale fluctuations

• Abundance of (mini)halos is modulated by large scale fluctuations

→ scale-dependent halo bias

Dalal+(2008); Slosar+(2008)
Application (2):
Primordial non-Gaussianity (cont’d)

Forecasted constraints

- SKA
  \[ \Delta f_{\text{NL}} = 0.7, \Delta g_{\text{NL}} = 2 \times 10^3 \]

- FFTT
  \[ \Delta f_{\text{NL}} = 0.1, \Delta g_{\text{NL}} = 7 \times 10^2 \]

- cf. Future CMB (COrE)
  \[ \Delta f_{\text{NL}} = 2, \Delta g_{\text{NL}} = 2 \times 10^4 \]

Minihalos potentially improve the (saturated) CMB bound by orders of magnitude
Summary

- Minihalos can probe primordial fluctuations at a wide range of scales, especially those at small scales (<<Mpc), which are difficult to be probed by other observations.

- 21cm signal from can probe primordial fluctuations with increased statistics and enhanced range of scales. Our formulation of tomographic angular spectrum can maximally exploit such advantage in minihalos.
  
  ▶ Spectral runnings of primordial spectrum

  ▶ Non-Gaussianity

- Lots of other cosmological applications (e.g. WDM [TS & Tashiro arXiv: 1401.5563]) can be considered.
backup slides
Details of calculation

21cm line signals from single minihalo

Based on Iliev+ (2002)

- minihalo has an inner structure
  → line of sight integral + average over cross-section

\[
\Delta T_b(M, z) = A^{-1} \int dA \int_0^{\tau(r)} d\tau \left[ T_S(\sqrt{r^2 + l(\tau)^2}) - T_{\text{CMB}} \right] e^{-\tau}
\]

with \( A = \pi r_h^2 \)

- halo profile: truncated isothermal sphere (TIS)
  Shapiro, Iliev & Raga (1999)

- spin temperature: strongly coupled with gas

\[ T_S \approx T_{\text{gas}} \]
21cm signal

contributions from single halo

rms of 21cm fluctuations (SKA-like survey with $\Delta \theta=9'$, $\Delta \nu=1$MHz)

21cm signal from minihalos can be observed by SKA

- case 1: PS & $\delta_c=1.67$
- case 2: PS & $\delta_c=1.52$
- case 3: ST & $\delta_c=1.67$
- case 4: ST & $\delta_c=1.52$
Specification of surveys

<table>
<thead>
<tr>
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<th>SKA</th>
<th>FFTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>total effective area $A_{\text{tot}}$ [m$^2$]</td>
<td>$10^5$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>bandwidth $\Delta \nu$ [MHz]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>beam width $\Delta \theta$ [arcmin]</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>integration time $t$ [hour]</td>
<td>1000</td>
<td></td>
</tr>
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</table>

Table 1. Specification of 21 cm surveys.

<table>
<thead>
<tr>
<th></th>
<th>Planck</th>
<th></th>
<th></th>
<th>COrE</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>band frequency [GHz]</td>
<td>100</td>
<td>147</td>
<td>217</td>
<td>105</td>
<td>135</td>
<td>165</td>
<td>195</td>
<td>225</td>
</tr>
<tr>
<td>beam width $\Delta \theta$ [arcmin]</td>
<td>9.9</td>
<td>7.2</td>
<td>4.9</td>
<td>10.0</td>
<td>7.8</td>
<td>6.4</td>
<td>5.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Temperature noise $\Delta T$ [$\mu$K arcmin]</td>
<td>31.3</td>
<td>20.1</td>
<td>28.5</td>
<td>2.68</td>
<td>2.63</td>
<td>2.67</td>
<td>2.63</td>
<td>2.64</td>
</tr>
<tr>
<td>Polarization noise $\Delta P$ [$\mu$K arcmin]</td>
<td>44.2</td>
<td>33.3</td>
<td>49.4</td>
<td>4.63</td>
<td>4.55</td>
<td>4.61</td>
<td>4.54</td>
<td>4.57</td>
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</table>

Table 2. Specification of CMB surveys.
Blue-tilted isocurvature power spectrum
Isocurvature perturbations

Relative perturbations between matter and radiation

\[ S(\vec{x}) = \delta \log \left( \frac{n_{\text{matter}}(\vec{x})}{n_{\text{rad}}(\vec{x})} \right) \]

Theoretical models: axion (uncorrelated), curvaton (correlated), ...

Power spectrum

\[ P_S(k) \propto \alpha k^{p-1} \]

\[ \alpha = P_S(k_0)/P_\zeta(k_0) \quad \text{at } k_0=0.002\text{Mpc}^{-1} \]

Blue spectrum (e.g, Kasuya & Kawasaki ‘09) is less constrained from CMB C{l}
Matter power spectrum

Takeuchi & Chongchitnan (2013)
Effects on mass function

- Small $\alpha$: abundance of halos increases at all $M$ as $\alpha$ increases
- Large $\alpha$: abundance of small halos starts to decrease
  ← incorporation of smaller haloes into larger ones

Mass function does not change monotonically:

- Small $\alpha$: abundance of halos increases at all $M$ as $\alpha$ increases
- Large $\alpha$: abundance of small halos starts to decrease
  ← incorporation of smaller haloes into larger ones
Constraint from reionization

Isocurvature pert. with blue spectrum can promote reionization

• Simplified modeling of reionization Tegmark & Silk (1994)

\[ x_{\text{reion}} = f_{\text{coll}} \frac{\Delta m_p c^2}{13.6 \text{eV}} f_{\text{burn}} f_{\text{UV}} f_{\text{esc}} f_{\text{ion}} \]
\[ = f_{\text{net}} \sim 10^{-4} \]

collapsed baryon fraction in massive halos

for Pop II model
(Sommerville & Lavio 2003)

• Constraints from \( \tau_{\text{reion}} \)

→ Tighter constraints than from \( C_l^{TT} \)
(even with the large uncertainty in \( f_{\text{net}} \))

allowed by CMB (WMAP9+ACT +SPT)

excluded by \( \tau_{\text{reion}} < 0.13 \)
21cm fluctuations from minihalos

Complicated response to $\alpha$:
- small $\alpha \rightarrow$ increase in mass function
- intermediate $\alpha \rightarrow$ decrease in mass function at $M<10^8\text{M}_\odot$
- large $\alpha \rightarrow$ increase in matter fluctuations at resolved scales ($\sim$Mpc)
21cm line fluctuations & reionization optical depth can complementarily constrain isocurvature perturbations
Warm dark matter
Warm dark matter?

**Motivation: small-scale problems**

- missing satellites
- cusp-core profile

**Models: thermal/non-thermal relics**

ex) sterile neutrino, gravitino, ...

- solution to small scale problems?

\[ m_{WDM} = \mathcal{O}(1) \text{keV} \]
Effects on structure formation

Matter power spectrum

suppressed within free-streaming scale

\[ \lambda_{FS} \simeq 0.1 \left( \frac{m_{WDM}}{1\text{ keV}} \right)^{-4/3} \text{ Mpc} \]

Mass function

- suppressed formation of small halos
- additional cut-off at \( \sim M(\lambda_{FS}) \) ?

\[ \text{Zavala+}(2009), \text{ Polisensky & Ricotti (2011)} \]

← break down of hierarchical formation
Current & Future constraint

Lyman-alpha forest

Narayanan+ (2000), Viel+ (2005), Seljak+ (2006), ...

- recent constraint: $O(1)$ keV

Iršič+ (2013): $m_{\text{WDM}} > 5.3\text{keV (2}\sigma)$

Abundances of GRB

de Souza+ (2013): $m_{\text{WDM}} > 1.6\text{keV (2}\sigma)$

Weak lensing

Euclid (forecast): $m_{\text{WDM}} > 2.6\text{keV (2}\sigma)$

Smith & Markovic (2011)
21cm fluctuations

- As WDM deviates from CDM ($m_{WDM} \rightarrow 0$), 21cm line fluctuations are suppressed.
- Sensitive to $m_{WDM} > 10$keV.
Forecast constraint

2σ lower bounds ($z_{\text{min}}=5$)

- **SKA-low**
  \[ m_{\text{WDM}} > 22 \text{keV} \]

- **FFTT**
  \[ m_{\text{WDM}} > 30 \text{keV} \]

cf. current constraint

\[ m_{\text{WDM}} > 3 \text{keV} \] (Ly\(\alpha \) forest)

→ WDM of O(10)keV may be probed and precluded from the solution of small-scale crisis
Further suppression effects?

Modification of halo profile

- Formation of small halos delays

\[ \langle 1 + z_{\text{coll}} \rangle(M) = \sigma_M / \delta_c \]

→ less concentration

- Thermal velocity

\[ vt \sim 0.5(1 + z)^{-1/2} \left( \frac{m_{\text{WDM}}}{1\text{keV}} \right)^{-4/3} \text{kpc} \]

→ cored profile

Smith & Markovic (2011)

$\log_{10}(M[h^{-1}M_\odot]) = 9$

increase $m_{\text{WDM}}$

0.25 → 1.25keV
Further suppression effects? (cont’d)

Relative difference from the baseline case

Additional effects unique to WDM are important only for $m_{\text{WDM}} < \text{a few keV}$ and negligible for $m_{\text{WDM}} > 10\text{keV}$
String wakes
String wakes: overview

- **Conical spacetime around a string**
  - deficit angle: \( \Delta \theta = 8\pi G \mu \)
  - \( \mu \): string tension
  - Matter gets velocity kick
  - \( v_{\text{kick}} = 4\pi G \mu v_s \gamma_s \)

- **Formation of string wakes and minihalos**
  - Matter accretes around trace of strings
    - sheet-like structure = wake
  - Shock front on wake surface \( \rightarrow \) thermalization
  - Instability of planar structure
    - fragmentation into minihalos (size \( \sim \) wake thickness)
Formation wakes
based on Duplessis & Brandenberger (2013)

• Zel’dovich approximation (in MD)

physical distance from wake

\[ r_{\text{phys}}(x_{\text{ini}}, t) = a(t)(x_{\text{ini}} + \psi(x_{\text{ini}}, t)) \]

\[ \frac{d^2 \psi}{dt^2} + \frac{3}{4t} \frac{d\psi}{dt} - \frac{2}{3t^2} \psi = 0 \quad \rightarrow \quad \psi \simeq -\frac{5}{3} v_{\text{kick}} t_{\text{ini}} \left( \frac{t}{t_{\text{ini}}} \right)^{3/2} \]

• Decoupling from global expansion → virialization

physical wake size \( \sim 1/2 \) turn around scale (\( \dot{r}_{\text{phys}} = 0 \))

\[ w(t) = \frac{5}{3} v_{\text{kick}} t_{\text{ini}} \left( \frac{t}{t_{\text{ini}}} \right)^{4/3} \propto a(t)^2 \]

Baryon is thermalized at shock on wake surface

\[ \frac{3}{2} k_B T = \frac{m_p}{2} v_{\text{surface}}^2 \quad \rightarrow \quad T = 10 \text{ K} \left( \frac{G\mu}{10^{-6}} \right)^2 (v_s \gamma_s)^2 \frac{z_{\text{ini}} + 1}{z + 1} \]
Formation of minihalos
based on Duplessis & Brandenberger (2013)

- **Wake volume in horizon**
  
  Fractional volume of wakes generated in $\Delta t_i$ at $t_i$
  
  $$\Delta f_i(t) = \frac{\gamma t_i \times v_s \gamma_s \Delta t_i \times w_i(t)a(t)^2/a_i^2}{t_i^3 a(t)^3/a_i^3}$$

  Scaling solution: # of strings in horizon
  
  $$= \gamma \sim O(1)$$

- **Fragmentation into minihalo**
  
  Time scale $\sim w_i(t)$ (Zel’dovich pancakes)
  
  $$\rightarrow V_i(t) = \frac{4\pi}{3} w_i(t)^3$$

  $$M_i(t) = 4\bar{\rho}(t)V_i(t)$$

- **Mass function**
  
  $$\frac{dn(M, t)}{dM} = \frac{a(t)^3}{V_i(t)} \frac{df_i(t)/dt_i}{dM_i(t)/dt_i}$$
mass function & gas temperature

- Mass of minihalos increases: absorption $\rightarrow$ emission in 21cm line
- Atomic cooling is ineffective
  $\rightarrow$ can be observed by 21cm line fluctuations

**Figure 3.** Mass function of dark matter halos for a string network with parameters $3.4$ (solid) and the Reed et al. [51] predictions (dashed) at different redshifts. The colors with largest wavelength corresponds to the largest redshifts.

Here, $\xi_{\text{crit}}(z) = 1.686(1 + z)$ and $(M)_{\text{rms}}$ is the rms density fluctuation on a comoving length scale $R = (3/M/4\pi)^{1/3}$ which depends on the power spectrum of matter. Figure 4 shows $F(M|\xi_{\text{crit}}(z))$ for three different values of $G\mu$. Here $M_{\text{w}}(z, G\mu)$ is the maximum mass of wake halos. We also plot $F(10^3 M/h, z)$ which was the smallest mass that was resolved in the simulation by Reed et al. [51]. If $F$ is close to 1, then most of the matter was accreted onto large Gaussian noise-induced halos, and therefore large halos wiped out any geometrical structures and spatial correlations that wake halos could possess. As the figure shows, the larger the redshift is, the less will be the washout of string-induced structures by the Gaussian noise.
21cm fluctuations

- string distributions
  \[ \rightarrow 21\text{cm line fluctuations} \]

- Upper bound on string tension
  SKA: \( G\mu < 4 \times 10^{-8} \) (2sigma)

\[ \Rightarrow \text{Strings with } G\mu = 10^{-7} \text{ (Planck upper bound) can be observed with SKA} \]