Probing dark energy and inflation with 21cm line observations

Toyokazu Sekiguchi
(RESCEU, Univ of Tokyo)
Plan of talk

• Introduction: 21cm line signals from IGM and minihalos

• Applications:
  » Primordial perturbations
  » Dark energy

• Summary

Refs:
  ❖ M. Kawasaki, TS, T. Takahashi [1104.5591]
Introduction

- Dark ages (Epoch of reionization)
  - CMB last scattering $z \sim 10^3$
  - reionization $z \sim 6$

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

Mao+ '08
Redshifted 21cm line surveys

- Ongoing
  - LOFAR, MWA, ...

- Near future
  - Square Kilometer Array (SKA-low)
    - 21cm line from 3<z<27;
    - phase 1 will start by 2023
  - Hydrogen Epoch Reionization Array (HERA)
    - main target: 21cm line from 7<z<12

- Far future
  - FFTT, Omniscope, Lunar telescope?
What do 21cm surveys observe?

- Spin temperature
  - Ratio of triplets to singlet
    \[ \frac{n_{\text{triplet}}}{n_{\text{singlet}}} = 3 \exp \left[ -\frac{E_{21\text{cm}}}{T_s} \right] \]
What do 21cm surveys observe?

- Spin temperature
  - Ratio of triplets to singlet
    \[ \frac{n_{\text{triplet}}}{n_{\text{singlet}}} = 3 \exp \left[ -\frac{E_{21\text{cm}}}{T_s} \right] \]

- Brightness temperature
  - Radiative transfer
    \[ T_{21\text{cm}}(\nu) = \frac{T_s(z_{\nu}) - T_{\text{CMB}}(z_{\nu})}{1 + z_{\nu}} (1 - e^{-\tau_{21\text{cm}}(\nu)}) \simeq (T_s - T_{\text{CMB}})\tau_{21\text{cm}} \]
    \[ \tau_{21\text{cm}}(\nu) = \int dl \frac{3A_{10} \lambda_{21\text{cm}}^2}{32\pi} \frac{n_{\text{HI}}(z_{\nu})}{T_s(z_{\nu})} \phi(\nu) \]

Emission if \( T_s > T_{\text{CMB}} \)
Absorption if \( T_s < T_{\text{CMB}} \)
Sources of 21cm line

✓ smooth IGM
✓ minihalos

$\delta_b$
21 cm fluctuation from IGM

- Differential brightness temperature
  \[ \Delta T_b = T_b - T_{CMB} \approx \frac{T_s - T_{CMB}}{1 + z} \tau_{21\text{cm}} \]
  At high redshifts \( z > 20 \) (prior to formation of first objects), \( T_s < T_{CMB} \).

- Fluctuations in 21 cm brightness temperature
  \[ \delta_{21\text{cm}} \approx \frac{T_{CMB}}{T_s - T_{CMB}} (\delta T_s - \delta T_{CMB}) + \delta n_{\text{HI}} - \frac{\hat{n} \cdot d\bar{v}_b/dr}{H} \]
  depends on \( \delta_b \)
  depends only on \( \delta_m \)
  \( \hat{n} : \) line-of-sight direction
  \( \mu = \hat{k} \cdot \hat{n} \)
  \( \propto \mu^2 \)

21 cm can probe \( \delta_b \), separately from \( \delta_m \).
IGM 21cm power spectrum

- Tomographic power spectrum

\[ \langle \delta T_b(\vec{k})\delta T_b(\vec{k}') \rangle = (2\pi)^3 \delta(\vec{k}_1 + \vec{k}_2) P(k_\parallel, k_\perp) \]

\[ P(k_\parallel, k_\perp) = P_{\delta\delta}(k) + 2\mu^2 P_{\delta\nu}(k) + \mu^4 P_{\nu\nu}(k) \]

- \[ \mu = k_\parallel / k \]

- \[ P_{S_m}(k_0) / P_{AD}(k_0) = 0.1 \text{ at } k_0 = 0.0002\text{Mpc}^{-1} \]

- \[ n_{iso} = 3 \]

CDM/baryon isocurvature perturbation can be distinguished by 21cm.
Distinguishing CDM and baryon isocurvature

• Fisher matrix analysis

\[ r_{\text{CI}} = \frac{P_{\text{CI}}(k_0)}{P_{\text{adi}}(k_0)}, \quad r_{\text{BI}} = \frac{P_{\text{BI}}(k_0)}{P_{\text{adi}}(k_0)} \quad k_0 = 0.002 \text{Mpc}^{-1} \]

2d constraints

Future 21 cm surveys can distinguish CI/BI if \( n_{\text{iso}} \gtrsim 2 \).

Kawasaki, TS, Takahashi 2011

*fiducial model: pure CI \((r_{\text{CI}}, r_{\text{BI}}) = (0.1, 0)\)
Redshifted 21cm line fluctuations can constrain early-type dark energy better than CMB.

Parameterized EoS

\[ w(z) = w_0 w_1 \frac{a^p + a_s^p}{w_1 a^p + w_0 a_s^p} \approx \begin{cases} w_0 & \text{(for } a \gg a_s) \\ w_1 & \text{(for } a \ll a_s) \end{cases} \]
Sources of 21cm line

✓ Minihalos

✓ Smooth IGM

Iliev+ ’02;
Furlanetto & Loeb ’02
Minihalos

Halos too small to host galaxies

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

- Mass: $10^4 \, \text{M}_{\odot} < M < 10^8 \, \text{M}_{\odot}$

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

- Abundant, even at high-$z$
21cm line signal from minihalos

“21cm forest” in CMB

- Minihalos create emission/absorption features in CMB spectrum at radio frequency $\nu = 1.4\text{GHz}/(1+z)$

- Large (small) halos appear as emission (absorption)

- Individual halos are too small (size~kpc) to be resolved
  $\rightarrow$ intensity maps (like CMB)

$Iliev+ '02$; $Furlanetto & Loeb '02$
N-body+hydro simulations Shapiro+ '06

Minihalos can exceed the IGM around the epoch of reionization

Semi-analytical description agrees with simulations
21cm angular power spectrum from minihalos (1)

Tomographic anisotropy (w/o redshift space distortion)

\[
\delta T_b(\hat{n}, \nu) = \int_{M_{\text{min}}}^{M_{\text{max}}} dM \, T_b^{(\text{single})}(M, z_{\nu}) \frac{dN(M, z_{\nu})}{dM} \, b(M, z) \left[ F_b(M, z) \delta(x = r_{\nu} \hat{n}, z_{\nu}) \right]
\]

- 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)

Iliev+ '02; TS, Takahashi, Tashiro & Yokoyama '17
21cm angular power spectrum from minihalos (2)  

Iliev+ ’02; TS, Takahashi, Tashiro & Yokoyama ’17

Redshift-space distortion (Kaiser effect)

$$\delta T_b(\hat{n}, \nu) = \overline{T}_b(z) \left[ \beta(z) + f(z) \mu^2 \right] \delta(\vec{x}, z)$$

mean signal: \(\overline{T}_b(z) = \int dM \mathcal{F}(M, z) = \int dM T_b^{(\text{single})}(M, z) \frac{dN}{dM}(M, z)\)

growth rate: \(f(z) = \frac{d \ln D(z)}{d \ln a}\)

flux-weighted effective bias: \(\beta(z) = \frac{1}{\overline{T}_b(z)} \int dM \mathcal{F}(M, z)b(M, z)\)

Tomographic angular power spectrum

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

with \(a_{lm}(z) = \int d\hat{n} \delta T_b(\hat{n}, \nu) Y_{lm}^*(\hat{n})\)
21cm angular power spectrum from minihalos (3)
Application (1): Primordial spectral runnings

Spectrum of primordial fluctuations

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

- 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 $\alpha_s$) $\rightarrow$ spectral shapes
- Higher order parameters (e.g. $\beta_s$) $\rightarrow$ overall amplitudes
  $\rightarrow$ 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.

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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)

\[
f_{NL} = 0.8 \pm 5.0, \quad g_{NL} = (9.0 \pm 7.7) \times 10^4
\]

cf. \(g_{NL} = (-3.3 \pm 2.2) \times 10^5\) (WMAP 9yr)

TS & Sugiyama ’13
Application (2):
Primordial non-Gaussianity (cont’d)

Effects of local-type non-Gaussianity on (mini)halos

• Correlation between large and small scale fluctuations

• relative halo # count \( \frac{n_{\text{halo}}(\bar{x})}{\rho_m} \) is modulated by large-scale fluctuations

\( \rightarrow \) scale-dependent halo bias \( \text{Dalal+ ’08; Slosar+ ’08} \)
Application (2): Primordial non-Gaussianity (cont’d)

Effects on minihalo power spectrum

Bias is more enhanced at larger scales

\[
\Delta \beta(k, z) \approx \{ \beta_f(z)f_{\text{NL}} + \beta_g(z)g_{\text{NL}} \} \frac{3\Omega_m H_0^2}{2k^2 T(k) D(z)}
\]

→ 21cm line surveys are advantageous

✓ large transverse scale comparable to CMB
✓ cross-correlation of different redshifts
Application (2): Primordial non-Gaussianity (cont’d)

Forecasted constraints

- Minihalos can improve the current (CMB) bound by orders of magnitude
  \[
  \Delta g_{NL} \simeq O(10^3), \Delta \tau_{NL} \simeq O(10) \quad \text{(for SKA)}
  \]

- Suyama-Yamaguchi inequality can be tested
Application to dark energy

**Constant EoS**

- SKA: $\Delta w \sim 0.05$
- FFTT: $\Delta w = 0.02$
- Cf. Planck: $\Delta w = 0.08$

Both CMB and 21cm suffer from the degeneracy between $w$ and the Hubble parameter.

Incorporation of direct Hubble measurements may be useful.

We will pursue our analysis with early-type DE in the future.
Summary

• High redshifted 21cm line fluctuations are a novel probe of the cosmological structure. There are largely two types of sources: smooth IGM and minihalos.

• Exploiting the tomographic nature of redshifted 21cm line fluctuations, we can constrain a variety of cosmological models.
  
  ▶ Primordial fluctuations (spectral runnings, non-Gaussianity, etc.)
  
  ▶ Dark energy

▶ (DM, neutrinos, etc)