Cosmology and high-redshift universe with the redshifted 21 cm line

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The early Universe: a laboratory for high-energy physics
Cosmology & high-energy physics

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- This talk: 21 cm experiments
The 21 cm line of neutral hydrogen (HI)

- Hydrogen 1s ground state split by the interaction between the electron spin and the nuclear spin.

\[
\begin{align*}
\text{unperturbed} & \quad \text{triplet} \\
1s & \quad \begin{cases}
|\uparrow \uparrow\rangle \\
\frac{1}{\sqrt{2}} (|\uparrow \downarrow\rangle + |\downarrow \uparrow\rangle) \\
|\downarrow \downarrow\rangle
\end{cases} \\
& \quad \begin{cases}
|\uparrow \downarrow\rangle \\
\frac{1}{\sqrt{2}} (|\uparrow \downarrow\rangle - |\downarrow \uparrow\rangle)
\end{cases} \\
& \quad \text{singlet}
\end{align*}
\]

\(\nu = 1420\text{ MHz, } \lambda = 21\text{ cm}\)

Line transition \(\rightarrow\) a transition originating at \(z\) will be observed at \(\nu_{\text{obs}} = 1420/(1 + z)\) MHz.

- It is a magnetic dipole transition, with transition probability \(A_{21} = 2.85 \times 10^{-15} \text{ s}^{-1}\) \(\rightarrow\) an atom in the upper level is expected to make a downward transition once in \(10^7\) yr.

- For instance, 21 cm radiation from galaxies allowed inference of dark matter (the rotation curves).
How to observe the cosmological 21 cm signal?

\[ \frac{n_2}{n_1} = 3 e^{-T_{\text{spin}}/T_{21}} \]

The signal:
\[ \delta l_\nu \propto \rho_{\text{HI}} \left( 1 - \frac{T_{\text{CMB}}}{T_{\text{spin}}} \right) \]
Some comments on the 21 cm signal

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  1. Mass of light dark matter particles using the global signal at $z \approx 18$ (the “cosmic dawn”).
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  2. Dark energy constraints using large-scale fluctuations in the HI density at $z \approx 0 - 2$. 
Global 21 cm signal: probe of the very first stars

\[ \delta T_b \propto \frac{T_s - T_{\text{CMB}}(z)}{T_s} \rho_{\text{HI}}, \quad T_s^{-1} = \frac{T_{\text{CMB}}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha} \]

Expected signal for a fiducial model of galaxy formation Pritchard & Loeb (2012)
Global 21 cm signal: probe of the very first stars

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**Expected signal for a fiducial model of galaxy formation Pritchard & Loeb (2012)**

Presence of UV radiation, arising from the first stars.
Gas is colder than CMB, so absorption.
Global 21 cm signal: probe of the very first stars

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Efficient heating of the gas, most likely by X-rays.
Formation of accreting black holes, supernova shocks.
Recent detection of the global 21 cm signal

EDGES experiment **Bowman et al (2018)**
The signal can be used to put constraints on the mass of (thermal) warm dark matter particles.
Power spectra for WDM models

\[ \delta(x) = \frac{\rho(x)}{\bar{\rho}} - 1 \]
\[ \delta(k) = \text{FT} \left\{ \delta(x) \right\} \]
\[ P(k) \propto |\delta(k)|^2 \]

Light keV mass dark matter particles have less fluctuations at small scales.
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Light keV mass dark matter particles have less fluctuations at small scales.
Warm dark matter particles ($m \sim \text{keV}$) suppress matter fluctuations at small scales.

Constraints from Lyman-forest $m \gtrsim 3.5 \text{keV}$ Murgia et al (2019).

However, constraints are degenerate with astrophysics (e.g., gas temperature) Garzilli et al (2019).

There are other similar dark matter candidates which exhibit similar behaviour (e.g., axion-like particles or “Fuzzy” dark matter).

Model-independent approach of parametrizing the suppression:

$$T(k) = [P(k)/P_{CDM}(k)]^{1/2} = 1 + (k)$$

Small-scale suppression

- Warm dark matter particles \((m \sim \text{keV})\) suppress matter fluctuations at small scales.
- Constraints from Lyman-\(\alpha\) forest \(m \gtrsim 3 - 5\ \text{keV}\)
  

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Model-independent approach of parametrizing the suppression:

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Constrain; from observations, agnostic to the dark matter model


\[ \Delta^2(k) \]

\[ k(h/\text{Mpc}) \]

\[ \text{CDM} \]

\[ 1 \text{ keV} \]

\[ 2 \text{ keV} \]
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- Model-independent approach of parametrizing the suppression:

\[
T(k) \equiv \left[ \frac{P(k)}{P_{CDM}(k)} \right]^{1/2} = [1 + (\alpha k)^\beta]^\gamma.
\]

Constrain \(\alpha, \beta, \gamma\) from observations, agnostic to the dark matter model Murgia et al (2018).
Halo mass function for WDM models

$z = 9.0$

fitting functions from Schneider et al (2012)
Halo mass function for WDM models

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Galaxy formation models

Present observations detect only the very bright galaxies, hence unable to distinguish between different DM models.

WDM effects degenerate with astrophysical effects (feedback).

Dayal, TRC, Bromm & Pacucci (2017)
Hierarchical structure formation: CDM

- Time progression:
  - No stars
  - First stars
  - Normal

Diagram:

- First stars branch:
  - No stars
  - First stars
- Normal branch:
  - First stars
  - First stars
  - First stars

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Hierarchical structure formation: WDM

First stars

Time
WDM models vs EDGES data

Observations require $m_{DM} \geq 3$ keV Chatterjee, Dayal, TRC & Hutter (2019)

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Future

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- More information in 21 cm fluctuations using interferometers, e.g., GMRT (near Pune) and SKA (international project with India as a partner)

Based on TRC & Paranjape (2018)
The uGMRT

- The upgraded Giant Metrewave Radio Telescope
- 30 antennas, 45 m diameter each. works in frequency range $\approx 150 - 1400$ MHz
- situated at Narayangaon, about 80 km from Pune.
The Square Kilometre Array

- dishes in South Africa, called SKA-MID (250 MHz – 20 GHz)
- dipoles in Australia, called SKA-LOW (50 – 250 MHz)
- largest distance between antenna elements: ~ 60 – 150 km
- effective collecting area ~ 5 – 10 times more collecting area than any existing telescope!
- possible observations from 2027-2030.
India has been associated with the SKA from the beginning

- India formally joined the SKA on Oct 5, 2015
- The activities within India are coordinated by the SKA-India Consortium
- ~20 organizations are members of the Consortium
- Science activities coordinated by eight SKA-India Science Working Groups
- India involved in all the key science projects in the SKA
HI intensity mapping

Based on ideas presented in Bharadwaj & Sethi (2001)

Probe the distribution only at large scales, adequate for cosmology.
Cosmology with HI intensity mapping

Santos et al (2015)
Take-home messages

- 21 cm signal from neutral hydrogen is a useful probe of cosmology
- The recently detected global signal, if confirmed, contain clues on the nature of light dark matter particles.
- In the future, fluctuations will be detected with the SKA. Should allow us to constrain cosmological parameters and any non-standard extensions to the $\Lambda$CDM model.
- Caveat: astrophysics can affect the conclusions!
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Thank you