A halo model for cosmological neutral hydrogen

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21- cm cosmology

Tomography: each frequency is a different epoch

N $\sim 3 \times 10^{16}$ modes, much smaller scales than CMB

[Loeb & Zaldariagga (2004)]

[Loeb (2006)]
Efforts to map the neutral hydrogen distribution

- SKA (South Africa/Australia)
- GMRT (Pune, India)
- LOFAR (Netherlands)
- PAPER, MEERKAT (South Africa)
- BINGO, CHIME, TianLai, HIRAX…
Predictions for (post-reionization) HI observations, all scales including nonlinear scales

Efficiently model the astrophysics
The halo model : rationale

[e.g. Cooray & Sheth (2002)]
The halo model: rationale

❖ Powerful tool in cosmology to discuss non-linear gravitational clustering
❖ Three ingredients: Halo mass function, halo bias and halo profile
❖ Describes abundance and clustering of dark matter, also used widely for galaxy evolution

Can we develop a halo model framework for neutral hydrogen?

Can we constrain it with the latest observations?
Surveying the data
Surveying the data

21 cm emission

21 cm intensity mapping

DLA HI absorption
Surveying the data

21 cm emission
- WHISP column density [Zwaan+ (2005b)]
- HIPASS mass function [Zwaan+ (2005a)]
- ALFALFA clustering, bias [Martin+ (2012)]

21 cm intensity mapping

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- GBT/DEEP2 [Switzer+ (2013)]

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DLA HI absorption
- Mg II selected: $z \sim 1$ [Rao+ (2006)]
- $z \sim 2.3$ bias [Font-Ribera+ (2012)]
- $z \sim 2.3$ SDSS [Noterdaeme+ (2012)]
- $z \sim 5$ GGG survey [Crighton+ (2015)]
- $z \sim 0-4$ incidence [Zafar+ (2013)]
The HI halo model

*Painting neutral hydrogen on dark matter*
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Two HI ingredients
The HI halo model

*Painting neutral hydrogen on dark matter*

**Two HI ingredients**

\[ M_{\text{HI}}(M, z) \]

How much HI is associated with a mass M halo?
The HI halo model

*Painting neutral hydrogen on dark matter*

**Two HI ingredients**

\[ M_{HI}(M, z) \]

How much HI is associated with a mass \( M \) halo?

\[ \rho_{HI}(r, M, z) \]

How is HI distributed in the halo?
The HI halo model

How much HI is associated with a mass $M$ halo? How is HI distributed in the halo?

from which we can derive HI observables

$M_{\text{HI}}(M, z)$  $\rho_{\text{HI}}(r, M, z)$


Painting neutral hydrogen on dark matter
The HI-halo mass relation

\[ M_{\text{HI}}(M) = \alpha f_{H,c} M \left( \frac{M}{10^{11} h^{-1} M_\odot} \right)^\beta \exp \left[ - \left( \frac{v_{c0}}{v_c(M)} \right)^3 \right] \]
The HI-halo mass relation

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Overall normalization; fraction of hydrogen relative to cosmic

Slope

Lower cutoff

HP, Refregier, Amara (2016)

HI radial profile

Exponential:
HI radial profile

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\[ \rho_{\text{HI}}(r, M) = \rho_0 \exp(-r/r_s) \]

[HP, Refregier, Amara (2016)]

HI radial profile

Exponential:

$$\rho_{\text{HI}}(r, M) = \rho_0 \exp\left(-\frac{r}{r_s}\right)$$

The viral radius-scale radius relation

[HP, Refregier, Amara (2016)]

HI radial profile

Exponential:

$$\rho_{\text{HI}}(r, M) = \rho_0 \exp(-r/r_s)$$

$$r_s \equiv R_v(M)/c_{\text{HI}}(M, z)$$
HI radial profile

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The concentration parameter and evolution

[HP, Refregier, Amara (2016)]

HI radial profile

Exponential:

\[ \rho_{\text{HI}}(r, M) = \rho_0 \exp\left(-\frac{r}{r_s}\right) \]

\[ r_s \equiv \frac{R_v(M)}{c_{\text{HI}}(M, z)} \]

\[ c_{\text{HI}}(M, z) = c_{\text{HI},0} \left( \frac{M}{10^{11} M_\odot} \right)^{-0.109} \frac{4}{(1 + z)^\gamma} \]

[HP, Refregier, Amara (2016)]


[Maccio+ (2007)]
HI radial profile

Exponential:

\[ \rho_{\text{HI}}(r, M) = \rho_0 \exp\left(-\frac{r}{r_s}\right) \]

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\[ c_{\text{HI}}(M, z) = c_{\text{HI,0}} \left( \frac{M}{10^{11} M_\odot} \right)^{-0.109} \left( \frac{4}{(1 + z)^{1.75}} \right) \]

Also considered an altered NFW profile:

\[ \rho_{\text{HI}}(r, M) = \frac{\rho_0 r_s^3}{(r + 0.75 r_s)(r + r_s)^2} \]

[Helfer & Refregier, Amara (2016)]


[Maccio+ (2007)]
Clustering

[HP, Refregier, Amara (2016)]

The HI profile

\[
\begin{align*}
  u_{\text{HI}}(k|M) &= \frac{4\pi}{M_{\text{HI}}(M)} \int_0^{R_v} \rho_{\text{HI}}(r) \frac{\sin kr}{kr} r^2 \, dr \\
  P_{1h,\text{HI}} &= \frac{1}{\bar{\rho}_{\text{HI}}^2} \int dM \, n(M) \, M_{\text{HI}}^2 |u_{\text{HI}}(k|M)|^2 \\
  P_{2h,\text{HI}} &= P_{\text{lin}}(k) \left[ \frac{1}{\bar{\rho}_{\text{HI}}} \int dM \, n(M) \, M_{\text{HI}}(M) \, b(M) \, |u_{\text{HI}}(k|M)| \right]^2 \\
  \xi_{\text{HI}}(r) &= \frac{1}{2\pi^2} \int k^3 (P_{1h,\text{HI}} + P_{2h,\text{HI}}) \frac{\sin kr \, dk}{kr} \frac{1}{k}
\end{align*}
\]
Constraining the parameters: MCMC

\[ M_{\text{HI}}(M) = \alpha f_{\text{HI}} c M \left( M/10^{11} h^{-1} M_\odot \right)^\beta \exp \left[ -\left( v_{c0}/v_c(M) \right)^3 \right] \]

\[ \rho_{\text{HI}}(r) = \rho_0 \exp(-r/r_s); \]

\[ c_{\text{HI}}(M, z) \equiv R_v/r_s = c_{\text{HI}, 0} \left( M/10^{11} M_\odot \right)^{-0.109} 4/(1 + z)^{1.09} \]

\[ c_{\text{HI}, 0} = 28.65 \pm 1.76 \]

\[ \alpha = 0.09 \pm 0.01 \]

\[ \log v_{c, 0} = 1.56 \pm 0.04 \]

\[ \beta = -0.58 \pm 0.06 \]

\[ \gamma = 1.45 \pm 0.04 \]

[HP, Refregier, Amara (2016)]
Data: low redshifts

- Westerbork Survey — spirals and irregulars (WHISP) [Zwaan+ (2005b)]
- HIPASS survey mass function [Zwaan+ (2005a)]
- Clustering of HI-rich galaxies - ALFALFA [Martin+ (2012)]
Data: intermediate redshifts

- Intensity mapping measurements with DEEP2/GBT survey [Switzer+ (2013)]
- Mg II selected DLA galaxies at redshifts $\sim 1$ [Rao+ (2006)]

INDEPENDENT MEASUREMENTS, BOTH MATCHED WELL BY HALO MODEL
Data: high redshifts

- Damped Lyman-alpha systems
- Column density distributions, incidences (SDSS, UVES, Gemini GMOS survey...)

![Graph showing log \(10\left( f_{HI}/\text{cm}^2 \right) \) vs. log \(10\left( N_{HI}/\text{cm}^{-2} \right) \) at redshifts \( z \sim 2.3 \) and \( z \sim 5 \). Noterdaeme+ (2012) and Crighton+ (2015).]
Best fit halo model

[HP, Refregier, Amara (2016)]
Best fit halo model

Non-unit slope, exponential profile
Consistent with abundance matching, stellar-cold gas relations

[HP, Refregier, Amara (2016)]
[HP & Kulkarni (2016)]
What do we learn?
Insights from the modelling
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- HIHM relations adopted in the literature [Barnes & Haehnelt 2014; Bagla + (2010)]
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- Combining the relations [HP, Choudhury, Refregier, MNRAS (2016)] does not fit HI mass function well
Insights from the modelling

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- Fitting the mass function requires a **non-unit slope** of HIHM [HP & Refregier, MNRAS (2017)]
Insights from the modelling

- HIHM relations adopted in the literature [Barnes & Haehnelt 2014; Bagla + (2010)]
- Combining the relations [HP, Choudhury, Refregier, MNRAS (2016)] does not fit HI mass function well
- Fitting the mass function requires a non-unit slope of HIHM [HP & Refregier, MNRAS (2017)]
- An exponential profile reduces previously observed tension between the HIHM and the column density [HP, Refregier, Amara (2016)]
Consistency with other observations

- Low-redshift observations for the HI surface density
  [Bigiel & Blitz (2012), Leroy+ (2008)]
- Anti-correlation between impact parameter - column density of DLAs
  [Rao+ (2011), Krogager+ (2012), Peroux + (2013)]
- Impact parameter - covering fractions of DLAs [Rudie+ (2012)]
Forecasting

- Observed angular power spectrum constraining cosmological parameters
- Explored degradation with the astrophysics - SKA 1 MID, $z \sim 0.35$, 1 Ghz, observing time 1 year with frequency interval 1 Mhz over 25000 sq. deg
- Fisher and MCMC forecasts quantitatively similar

\[
\Delta C_\ell = \left( \frac{2}{2\ell + 1} \right) (f_{\text{sky}} \Delta \ell)^{-1/2} (C_\ell + N)
\]

\[
N = \left( \frac{\Delta T_{\text{pix}}}{T} \right)^2 \Omega_{\text{pix}} W_\ell^{-1}
\]

\[
W_\ell = \exp -\ell^2 \sigma_{\text{beam}}^2 ; \quad T_{\text{sys}} = T_{\text{inst}} + T_{\text{sky}}
\]

2 astrophysical and 2 cosmological parameters
Forecasting
Forecasting

Astrophysical degradation ...

\[ z = 0.1 \quad \text{and} \quad z = 0.35 \]
Forecasting

Astrophysical degradation ... alleviated by tomography
To summarize ...
Conclusions and outlook
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- Built a framework for halo model of cosmological HI
- Two important ingredients: (i) HI-halo mass relation and (ii) HI profile
- Constrained well by emission line experiments, high redshift DLA data, intensity mapping data
- Best fitting HIHM and profile obtained by Bayesian analysis
- Model predictions consistent with
  (i) abundance matching and stellar-cold gas relations
  (ii) low-redshift observations for the HI surface density
  (iii) Impact parameter-covering fraction results for DLAs
- Build forecasts for the SKA, evaluate astro degradation and alleviation from tomography
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THANK YOU!