Fast Simulation of Cosmological Neutral Hydrogen with a Halo Model Approach

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Overview

• Fast and large volume simulations of neutral hydrogen (HI) distribution
• Test instrument simulation and analysis pipeline to measure the HI emission
PINOCCHIO: Dark Matter Halo Simulation

• Monaco et al. (2002, 2013), Taffoni et al. (2002), Munari et al. (2017)
• Lagrangian Perturbation Theory
• Collapsed points grouped into halos, hierarchical growth
• Catalog of dark matter halos
• Much faster than N-body
Current Setting of DM Simulations

• 500 Mpc/h box size
• $2048^3$ simulation particles
• $\geq 10$ particles per halo $\leftrightarrow \geq 1.27 \times 10^{10} \, M_\odot /h$

$\rightarrow 20 - 30\%$ HI mass missing

• Lightcone settings:
  - Frequency range: 700 – 800 MHz $\leftrightarrow$ Redshift 0.77 – 1.03
  - Half sky

• Euler Cluster of ETHZ (CPU) with MPI parallelization
  - 1032 cores over 39 nodes
  - 2.75 TB RAM, 332 CPU h runtime
Halo Model for Cosmological HI

HI-halo mass relation fitted to observations:

\[ M_{\text{HI}}(M, z) = \alpha f_{\text{HI}} M \left( \frac{M}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp \left[ -\left( \frac{v_{c,0}}{v_c(M, z)} \right)^3 \right] \]

Padmanabhan et al. 2017

- More massive halos contain more HI
- **But:** Many more small halos than large ones
  - Important not to neglect small halos.
Relative Loss of Total HI Mass

Relative loss as fct. of $z$ for different $M_{\text{min}}$

- $M_{\text{min}} = 10^9 \, M_\odot$/h
- $M_{\text{min}} = 10^{9.5} \, M_\odot$/h
- $M_{\text{min}} = 10^{10} \, M_\odot$/h
- $M_{\text{min}} = 1.27 \cdot 10^{10} \, M_\odot$/h
- $M_{\text{min}} = 1.5 \cdot 10^{10} \, M_\odot$/h
- $M_{\text{min}} = 10^{11} \, M_\odot$/h
Brightness Temperature Maps

- Redshift:
  - 0.8
  - 0.9
  - 1.0

- Frequency:
  - 800 MHz
  - 750 MHz
  - 700 MHz

- Temperature:
  - 0.03 mK
  - 0.50 mK

- Δf = 5 MHz
- Δz ~ 0.01
HI Angular Power Spectrum

Simulation:

\[ \delta_{HI} = (T_{HI} - \bar{T}_{HI}) / \bar{T}_{HI} \]

\[ \langle \delta_{HI, \ell m} \delta_{HI, \ell' m'}^* \rangle = \delta_{\ell \ell'}^D \delta_{mm'}^D C_{\ell, HI} \]

Limber Approximation:

\[ C_{\ell, HI} \approx \int dz \frac{c}{H(z)} \frac{W^2(z)}{r(\chi(z))^2} P_{HI} \left( \ell + \frac{1}{2}, r(\chi(z)), z \right) \]

Refregier et al. 2017
HI Angular Power Spectrum

Simulation:

\[ \delta_{HI} = \frac{T_{HI} - \bar{T}_{HI}}{\bar{T}_{HI}} \]
\[ \langle \delta_{H1,\ell m} \delta_{H1,\ell' m'}^* \rangle = \delta_{\ell \ell'}^D \delta_{mm'}^D C_{\ell,HI} \]

Limber Approximation:

\[ C_{\ell,HI} \approx \int dz \frac{c}{H(z)} \frac{W^2(z)}{r(\chi(z))^2} P_{HI}(\ell + 1/2, z) \]

Full Expression:

\[ C_{\ell,HI} = \frac{2}{\pi} \int k^2 dk \int_0^\infty d\chi W(\chi) j_\ell(k\chi) \sqrt{P_{HI}(k, z(\chi))} \]
\[ \times \int_0^\infty d\chi' W(\chi') j_\ell(k\chi') \sqrt{P_{HI}(k, z(\chi'))} \]
HI Power Spectrum

$P_{HI}(k, z = 1.0220)$

$P_{HI}(k)$ vs. $k$ (Mpc$^{-1}$)

- Simulation
- PyCosmo Halo Model

<table>
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<th>Rel. Diff.</th>
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<td>+ positive</td>
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<td>- negative</td>
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Snapshot at $z = 1.022$
HI Angular Power Spectrum

Full Expression:

\[ C_{\ell, \text{HI}} = \frac{2}{\pi} \int_0^\infty k^2 \, dk \int_0^\infty d\chi \, W(\chi) j_\ell(k\chi) \sqrt{P_{\text{HI}}(k, z(\chi))} \times \int_0^\infty d\chi' \, W(\chi') j_\ell(k\chi') \sqrt{P_{\text{HI}}(k, z(\chi'))} \]
Instrument Simulation and Analysis Pipeline

Number of dishes: 36 (6 x 6 grid)
Operating mode: Drift-scan
Dish diameter: 6 m
Dish separation: 6 m
Primary Beam Type: Gaussian
Telescope Latitude: 45°

- Construct instrument model
- Generate synthetic data: Visibilities
- Map Making

Simplified HIRAX array configuration

Recovered Map

Angular Power Spectrum

0 mK 0.5806
Recovered HI Angular Power Spectrum

\[ f \text{ [MHz]} \in [700, 705] \text{ or } z \in [1.015, 1.029] \]

\[ f \sim \frac{2\pi f}{c} b \]

\[ \ell_{\text{max}}(700 \text{ MHz}) \sim 620 \]

\[ \ell_{\text{E-W}}(700 \text{ MHz}) \sim 440 \]
Summary

• Simulation pipeline of HI maps for intensity mapping
• Apply it to HIRAX and SKA/MeerKAT
• Theoretical predictions of power spectrum
• Future developments:
  – Increase mass resolution
  – Vary cosmology and astrophysics (HI-Halo mass relation)
  – Consider foregrounds, noise and RSD
  – Cross-correlations with other probes

Hitz et al. (in prep.)
Backup Slides
PyCosmo HI Halo Model: Angular Power Spectrum

\[ C_{\ell,\text{HI}} \approx \int dz \frac{c}{H(z)} \frac{W^2(z)}{r(\chi(z))}^2 P_{\text{HI}} \left( \frac{\ell + 1/2}{r(\chi(z))}, z \right) \]

\[ P_{\text{HI}}(k) = P_{1\text{h,HI}}(k) + P_{2\text{h,HI}}(k) \]

\[ P_{1\text{h,HI}} = \frac{1}{\bar{\rho}_{\text{HI}}^2} \int dM \frac{dn(M,z)}{dM} M_{\text{HI}}^2(M) |u_{\text{HI}}(k|M)|^2 \]

\[ P_{2\text{h,HI}} = P_{\text{lin}}(k) \left[ \frac{1}{\bar{\rho}_{\text{HI}}} \int dM \frac{dn(M,z)}{dM} M_{\text{HI}}(M) b(M) |u_{\text{HI}}(k|M)| \right]^2 \]