HYDROGEN AS A COSMOLOGICAL PROBE

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Bologna Joint Astrophysical Colloquium
28-03-2019
Neutral Hydrogen (HI) as a cosmic tracer

\[ \Omega_{HI} \sim \Omega_{\gamma} \sim \Omega_{*} \]

- Mild or no evolution over 12 Gyrs (in the same period UV, thermal state star formation change dramatically).

- Most of the HI (in mass) associated to Damped Lyman-Alpha systems, most of the HI (in volume) probed by the Lyman-alpha forest.
Fitting this simple statistics is already challenging for model builders: both SAMs or hydro sims do require some fine tuning.

Post processing is needed (i.e. neutral hydrogen self shielding, galactic feedback, radiative transfer, etc.) and also accurate tests of numerical convergence.

"typical" semi-analytical galaxy formation trend
The Lyman-alpha forest

- **Intergalactic medium**: filaments at low density (outside galaxies) – distances spanned 0.1–100 Mpc/h

- Lyman-alpha forest its the main manifestation of the IGM

- High redshift observable, 1D projected power (but also 3D)
**Intensity mapping**

**Linear theory model:**

\[
P_{21 \text{ cm}}(k, \mu, z) = \bar{T}_b(z)^2 [(b_{H_1}(z) + f(z)\mu^2)^2 P_m(k, z) + P_{SN}(z)].
\]

- \(\bar{T}_b(z) = 189 h \left( \frac{H_0(1+z)^2}{H(z)} \right) \Omega_{H_1}(z) \text{ mK},\)

- \(\Omega_{H_1}(z) = \frac{1}{\rho_c^0} \int_0^\infty n(M, z)M_{H_1}(M, z) dM,\)

- \(b_{H_1}(z) = \frac{1}{\rho_c^0 \Omega_{H_1}(z)} \int_0^\infty n(M, z)b(M, z)M_{H_1}(M, z) dM,\)

- \(P_{SN}(z) = \frac{1}{(\rho_c^0 \Omega_{H_1}(z))^2} \int_0^\infty n(M, z)M_{H_1}^2(M, z) dM,\)

- degeneracy between \(b_{H_1}\) and \(\Omega_{H_1}\), which can be broken by using other probes (cross-corr.)

- Progress made mainly in the modelling and in determining the low-z HI bias (~0.8) from observations (Obuljen+18)

- **IM signal:** main ingredient is the function \(M_{HI}(M_{halo})\) with its scatter.

\[
M_{H_1}(M, z) = M_0 \left( \frac{M}{M_{min}} \right)^\alpha \exp\left(-\frac{M_{min}}{M}\right)^{0.35}.
\]

\(M_{min}\) decreases with redshift, alpha increases with redshift.

Villaescusa-Navarro+18
Towards a consistent model

\[ \delta = -1 \rightarrow \delta \sim 30 \rightarrow \delta \sim 100 \]
Some key questions

• Is there a consistent model of HI evolution from $z=1100$ to $z=0$? What are the observables we *cannot* fit?

• To what extent HI traces the underlying structure formation process? Scale dependent bias? HI halo model? Shot noise?

• To what extent HI evolution is influenced by galaxy formation?

• Can we constrain feedback models?

• Is there evidence of new physics?

   **NEUTRINO MASSES, GEOMETRY OF THE UNIVERSE, DARK MATTER NATURE?**
### COMPUTATIONAL METHODS

<table>
<thead>
<tr>
<th><strong>ABSORPTION</strong></th>
<th><strong>EMISSION</strong></th>
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<tbody>
<tr>
<td>Investigated with hydro sims. down to $M_{\text{gas}} = 1.04 , M_{\text{sun}}$. (DM only not working).</td>
<td>Investigated with hydrosims down to $M_{\text{gas}} = 1.06 - 7 M_{\text{sun}}$. DM only simulations also working and still used.</td>
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**High resolution needed**, combination of low-res high-res very interesting for future and present 1D/3D flux power self consistent modelling.

Semi-analytical models could achieve a 10% agreement with observations.

Halo-model of forest absorption also developed (Irsic & McQuinn 17).

1D flux power fit: typically ~20 parameters fit done with MCMC with a likelihood built on $O(tens)$ accurate hydro sims.

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**HI halo models** quite used by the community (allow to explore parameter space faster).

Forecast made using Fisher Matrix. Very little data available that are either able to constrain some parameters of the model or get an evidence for LSS contribution with cross-correlation.
ABSORPTION
Bolton+17, Sherwood simulation suite (PRACE call: 15 CPU Mhrs)
Puchwen+19, New simulations (PRACE call: 23 CPU Mhrs)
New PRACE runs down to $M_{\text{gas}} = 10^4 \ M_{\text{sun}}$
<table>
<thead>
<tr>
<th><strong>Low resolution</strong> BOSS and SDSS-III spectra</th>
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<tbody>
<tr>
<td>S/N~2-3</td>
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<tr>
<td>Used to detect BAOs at z=2.3 and correlations in the transverse direction</td>
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<td>Used to place stringent constraints on neutrino masses &lt;0.12 eV</td>
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<tr>
<th><strong>Medium resolution</strong> X-Shooter VLT spectra</th>
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<tr>
<td>S/N ~ 30</td>
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<tr>
<td>100 spectra at z&gt;3.5</td>
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<td>Used to place stringent constraints on Warm Dark Matter in combination with high res. spectra</td>
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<tr>
<th><strong>High resolution</strong> VLT or Keck spectra</th>
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<tr>
<td>S/N ~100 - ~hundreds of spectra</td>
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<tr>
<td>Used for WDM, astrophysics of the IGM and galaxy formation, variation of fundamental constants</td>
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</tbody>
</table>

**References**

- Busca+13, Slosar+14, Font-Ribera+14
- Palanque-Delabrouille+15
- Seljak+06, Baur+16, Yeche+17 etc.
- Irsic, MV+ 17a,17b
- Lopez+16, Irsic+16
- MV+05,08,13, Becker+11
- Yeche+17, Garzilli+18, Bosman+18
High vs low-z Lyman-alpha flux power

**High redshift:**
constraining reionization

Statistical error usually comparable or larger than known systematic errors

**Low redshift:**
constraining feedback

Known systematic errors usually larger than statistical errors
Lyman-alpha forest open issues

Overall broad consistency between LCDM model and Lyman-alpha flux statistics.

Several different groups running hydro sims for quantitative cosmological analysis of forest data (Lukic, Onorbe, Palanque-Delabrouille, etc.).

Critical areas for modelling/simulations:

1) high-redshift regime: UV/temperature fluctuations.
2) low and intermediate redshifts: galactic feedback, HeII reionization.
3) modelling several statistics at once (PDF, 1D, 3D, bispectrum) - self-consistent model of 3D and 1D flux power not addressed.
4) resolution under control @ k=0.1 s/km roughly scales of k ~ 10-20 h/Mpc @ z=2-6?
THE COSMIC WEB in WDM/LCDM scenarios

$z=0$

\[
\frac{T_x}{T_{\nu}} = \left( \frac{10.75}{g_{*}(T_D)} \right)^{1/3} < 1
\]

\[
k_{FS} = \frac{2\pi}{\lambda_{FS}} \sim 5 \text{ Mpc}^{-1} \left( \frac{m_x}{1 \text{ keV}} \right) \left( \frac{T_{\nu}}{T_x} \right)
\]

\[
\omega_x = \Omega_x h^2 = \beta \left( \frac{m_x}{94 \text{ eV}} \right)
\]

\[
\beta = \left( \frac{T_x}{T_{\nu}} \right)^3
\]

$z=2$

$z=5$

WARNING:

Numerical fragmentation is less of an issue for the Lyman-alpha forest flux, but still reaching convergence especially at high-z is demanding (voids contribute).

MV, Markovic, Baldi & Weller 2013
Markovic & MV, 2014
Smoothing scales

- Different physical scales (on top of instrumental resolution) affect the power spectrum cutoff:
  - **thermal**: instantaneous temperature at that redshift;
  - **Jeans**: scale due to gas pressure;
  - **filtering scale**: depends on all the previous thermal history;
  - **WDM cutoffs are basically redshift independent**
- Constraints are obtained from a full shape of the 1D flux power.

Irsic, MV+17
This lower limit is derived under some assumptions

1) Bayesian analysis

2) Bootstrap-derived covariance matrix from mock QSO sample with entries multiplied by 1.3

3) resolution corrections performed and particularly important at high-z & small-scales

4) limited exploration of z_reio Jeans smoothing
Likelihood greatly improves (shrinks) when combined with HIRES, pushing towards LCDM (cold).

**Increasing covariance matrix by 1.3 (for XQ-100) or applying weak priors on cosmo parameters does not impact (this is good).**

Limits are then: $> 1.4$, $> 4.1$, $> 5.3$ keV for the reference cases for XQ-100 (medium res.), HIRES/Keck (high res.) and combined, respectively.
Thermal history is the main nuisance. It is marginalized over but still quite sensitive to priors. For reference case $T_{\text{IGM}}(z)$ assumed to be a power-law (motivated by IGM physics), having this assumption lifted weakens the combined constrained to 3.5 keV. Key-aspect here: wide redshift range that allows to break degeneracies between WDM cutoff, Jeans pressure, filtering scale (all suppress power but differently in $z$).
Different data sets allow to break degeneracies

MEAN FLUX (quite constrained by obs.)
TEMPERATURE AT MEAN DENSITY
ANOTHER TEMPERATURE PARAM.
AMPLITUDE OF LINEAR POWER
SLOPE OF LINEAR POWER

Irsic, MV+17
Redshift coverage is important since it allows to break degeneracies.

Irsic, MV+17
Reionization - I: islands of neutral hydrogen surviving?
Reionization - II: temperature fluctuations

Onorbe+18: homogenous (left) vs. patchy reionization (right) with temperature fluctuations

**UVB fluctuations** decrease opacity in overdense regions with more sources of ionizing photons, and increase the opacity in underdense regions that are distant from sources.

**Temperature fluctuations**: overdense regions reionize early and are cold and opaque, while underdense regions reionize late and are hot and transparent.
• Small scale effects seem to be small (if any) and are likely not to spoil WDM constraints.

• Large scale effects will be constrained by data and significantly affect 3D and 1D power. However, BAO constraints are at $z=2.3$. 
\[ \nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu}, \]

\[ T^{\phi}_{\mu\nu} = g_{\mu\nu} \left( -\frac{1}{2} \partial_\rho \phi \partial^\rho \phi - \frac{1}{2} m^2 \phi^2 \right) + \partial_\mu \phi \partial_\nu \phi. \]

\[ ds^2 = -(1 + 2\Phi)dt^2 + a(t)^2(1 - 2\Phi)d\mathbf{x}^2. \]

\[ \phi = \frac{1}{\sqrt{2m}} (\varphi e^{-imt} + \varphi^* e^{imt}) \]

\[ i \left( \dot{\varphi} + \frac{3}{2} H \varphi \right) = -\frac{\partial^2 \varphi}{2a^2 m} + m\Phi \varphi. \]

\[ \rho_\phi \equiv m \varphi \varphi^*, \quad v_i \equiv \frac{\partial_i \{\text{arg}(\varphi)\}}{am} = -\frac{i}{2am} \left( \frac{\partial_i \varphi}{\varphi} - \frac{\partial_i \varphi^*}{\varphi^*} \right) \]

\[ \dot{v}_i + H v_i + \frac{v_j \partial_j v_i}{a} = -\frac{\partial_i \Phi}{a} + \frac{1}{2a^3 m^2} \partial_i \left( \frac{\partial^2 \sqrt{\rho_\phi}}{\sqrt{\rho_\phi}} \right) \]

\[ \dot{\rho}_\phi + 3H \rho_\phi + \frac{\partial_i (\rho_\phi v_i)}{a} = 0. \]

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15, Nori&Baldi 18
Scalar Dark Matter - II

\[ \delta_m = F \delta_\phi + (1 - F) \delta_c. \]

\[ \ddot{\delta}_\phi + 2H \dot{\delta}_\phi + \frac{c_s^2 k^2}{a^2} \delta_k - \frac{3}{2} H^2 \delta_m k = 0, \]

\[ \ddot{\delta}_c + 2H \dot{\delta}_c - \frac{3}{2} H^2 \delta_m k = 0. \]

\[ c_s^2 \equiv \frac{k^2}{4a^2m^2}, \quad \frac{k_J}{a} = \sqrt{Hm}. \]

Linear perturbation theory in CDM+scalar field model

Sound speed of scalar DM and Jeans scale definition

At \( k < k_J \) no pressure
At \( k > k_J \) pressure and oscillations no growth
Comoving Jeans \( k_J \sim a^{1/4} \) in MD
Important quantity is \( k_J \) at equival.
Simulating Scalar Dark Matter

Schive+ 14

• Very distinctive prediction: solitonic core (steep jump in density) with a simple numerical solution (e.g. Mocz+17, Schive+17, Marsh+15, Nori & Baldi 18).
• Stability of the core over cosmological times still an open issue.
• Size of the core $M_{\text{core}} \sim M_{\text{galaxy}}^{1/3}$.
• Claimed detection at $10^{-22}$ eV from Phornax.
• Searched in galaxies but not seen, however baryon might be an issue (Blum+17).
Quantum potential not small for matter power spectrum, especially at high redshift.

< 5% extra suppression induced by the Quantum Potential w.r.t. to the same simulation with just a linear cut-off of power.
New interest in FDM models. **VERY RICH IMPLICATIONS.**

WDM thermal IGM constraints translated into FDM constraints by mapping $k_{1/2}$: poor approximation for large axion masses $> 1.e-21$.

IGM constraints are >$2-4 \times 10^{-21} \text{ eV}$ - ruling out the window range $0.1-1 \times 10^{-21} \text{ eV}$ typically chosen to solve (putative) small scale LCDM crisis.
X-Shooter sample+HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)
X-Shooter sample + HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)

Unreasonably low temperatures? Maybe not (e.g. Boera et al. finds 7000 K) but then there is a “jump” at $z=4.6$
Non-cold Dark Matter at small scales - I: a new and more general approach

Standard approach

\[ T(k) = \left[ 1 + (\alpha k)^{2\nu} \right]^{-5/\nu} \]

Applies to thermal WDM (Fermi Dirac distribution)

\[ \nu = 1.12 \]

\[ \alpha = 0.049 \left( \frac{m_x}{1 \text{ keV}} \right)^{-1.11} \left( \frac{\Omega_x}{0.25} \right)^{0.11} \left( \frac{h}{0.7} \right)^{1.22} h^{-1}\text{Mpc} \]

New general approach

\[ T(k) = \left[ 1 + (\alpha k)^{\beta} \right]^\gamma \]

Applies to ?

The larger is beta, the flatter is the shape for \( k < k_{1/2} \); the larger is gamma, the steeper is the small-scale cutoff.

Murgia, Merle, MV +17
Simple parametrization proposed works well for:
- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixed models
- fuzzy dark matter
- ETHOS dark matter models
Non-Cold Dark Matter and constraints on the SHAPE of the cutoff

\[ \alpha < 0.03 \, \text{Mpc}/h \ (2\sigma) \]

\[ |\beta/\gamma| < 14 \]

R. Murgia
EMISSION
Simulating intensity mapping signal: the HI bias

- Modelling of HI distribution based on particles and hydrosims of different box sizes of 15, 30, 60, 120 Mpc/h linear size and different feedback implementation with and without galactic feedback (B60W with galactic winds, B60 without).

Villaescusa-Navarro, MV + 2014
Simulating intensity mapping signal: large scales

- Scale dependence bias also present in massive neutrino cosmologies.
- $M_{HI}(M)$ not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but Omega$_{HI}$ lower) - because small mass haloes are suppressed i.e. impact on $n_{HALO}(M)$.
- IM alone would provide constraint of about $\sigma(M_{nu}) = 30$ meV (not very constraining compared to other probes).
- Radiative transfer postprocessing important but does not impact much the limit above.
Villaescusa-Navarro, Alonso, MV, 2017
\[ \lim_{R \to \infty} P_{21\text{cm}, \text{obs}, 1D}(k_{||}, z) = \frac{1}{4\pi R^2} P_{21\text{cm}}(k_{||}, z) \]

Villaescusa-Navarro, Alonso, MV, 2017
## BAOs with SKA1-MID - IV

<table>
<thead>
<tr>
<th>$z$ range</th>
<th>$\langle z \rangle$</th>
<th>mask</th>
<th>$(C)$</th>
<th>$\sigma_\alpha$</th>
<th>$(C+N)$</th>
<th>$\sigma_\alpha$</th>
<th>$(C+N+FG)$</th>
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</thead>
<tbody>
<tr>
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<td>0.997 ± 0.012</td>
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<td>yes</td>
<td>1.004 ± 0.016</td>
<td>1.002 ± 0.026</td>
<td>1.002 ± 0.031</td>
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</table>
Simulating intensity mapping signal: small scales

- Modeling of HI halo important also for halo models - Surely affected by feedback but maybe also sensitive to DM nature?
- Large scatter in the HI density profile.
- Mass dependence and central vs. satellites galaxies important to compare with observations.

Villaescusa-Navarro+18 based on Illustris TNG
Simulating intensity mapping signal: small scales

- Shot noise level in HI quite different from the standard case of galaxies and haloes
- Good amount of HI substructure within each DM halo
- Note further that *numerical convergence of all quantities not fully achieved.*
Simulating intensity mapping signal: WDM

Probably able **to rule out a 4 keV WDM model** with 5000 hours of observations at \( z > 3 \), while a smaller mass of 3 keV, comparable to present day constraints, can be ruled out at more than 2 confidence level with 1000 hours of observations at \( z > 5 \) – Note that density inside haloes poorly modelled.
SUMMARY

• HI important cosmic tracer to perform quantitative cosmology especially at high redshift.

• From the forest: no support for neutrino masses larger than zero or non cold dark matter.

• New frontier for forest is the high redshift close to reionization and 3D/1D self consistent model.

• Mocking 21cm maps with N-body simulations with inputs calibrated with high-res hydro sims and/or semi-analytical models of structure formation is promising. However, Fingers of God effects would require modelling down to small scales.