Cosmology with HI intensity mapping surveys

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(on behalf of the SKA Cosmology working group)
The CMB has provided unprecedented cosmological constraints

Next step: high precision measurements of the 3d structure of the Universe across cosmic times

Radio surveys provide an unique opportunity...

~ 50% of the comoving size of the Universe!
Large fast simulations of the HI signal:
http://intensimapping.physics.ox.ac.uk
HI galaxy surveys...

- Require high signal to noise to make a detection of a galaxy
- Need high sensitivity to beat shot noise and cosmic variance
- Expensive!

SKA1 ~ $10^7$ galaxies over 5,000 deg$^2$
SKA2 ~ $10^9$ galaxies over 30,000 deg$^2$
Do we need to “see” galaxies?

- Scales of interest for cosmology are well beyond galaxy scales
- To observe Baryon Acoustic Oscillations (used to probe dark energy) we need:
  - Angular resolution ~ 30 arcmin
  - Frequency resolution ~ 2MHz

Acoustic feature at ~ 100 Mpc/h
“Standard ruler”

2-point correlation function

Comoving Separation (h⁻¹ Mpc)

SDSS: Eisenstein et al. 2005
Intensity mapping

- Give up detecting galaxies
- Look instead at the integrated line emission from many galaxies in one big pixel
- Just like the CMB but with 3d information (tomography)
- Why intensity mapping with HI?
  - More abundant
  - Low frequency → large beam (low resolution) → good for large surveys
  - Low frequency → minimal contamination from other lines

z ~ 0.6, 1 MHz slice (SKA 1)

Maps of intensity

Galaxies
The HI Intensity Mapping signal

- Assume all HI in galaxies (OK for $z < 4$)

\[
\bar{T}_{\text{HI}}(z) \propto \Omega_{\text{HI}}
\]

\[
\Omega_{\text{HI}} \equiv \frac{\rho_{\text{HI}}(z) \text{[comoving]}}{\rho_c(z = 0)}
\]
HI Power spectrum: proportional to dark matter on linear scales (bias!)

One pixel of (0.5 deg)$\times$(2 MHz) $\sim 10^4$ Mpc$^3$ contains $\sim 10^3$ halos with HI at z$\sim$1!

Assume: $M_{HI}(M_{\text{halo}})$ to calculate HI density and bias (impose a lower and upper mass cut to host HI)

Bias scale dependence from the SAX simulations (Obreschkow et al., ApJ 2009) ~ constant on large scales

Bias $\sim 1$ at z=1
Current measurements...

- GBT: HI cross-correlation with WiggleZ...

GBT (Switzer et al., 2013): $\Omega_{\text{HI}} \text{bias} \gg 0.6 \times 10^{-3}$ at $z \sim 0.8$

Crucial to have more detections, even if at low $z$...
Experiments...

- **Dish surveys**
  - Each pointing gives you 1 pixel on the sky
  - Resolution set by dish size
  - Brightness sensitivity does not depend on dish size
  - Scan large area of the sky
  - More dishes or feeds to increase survey speed?

- GBT (Chang et al.)
- Parkes

**BINGO** (Battye, et al., http://arxiv.org/abs/1209.1041)
Experiments...

- Interferometers
  - Provide higher resolution
  - Ideally minimum baseline ~ 10 m for large scales...

Dense aperture array systems

- CHIME (Canada)
- Tianlai (China)
SKA1 as an intensity mapping “machine”

- Provide a *tomographic* view of the Universe up to high redshifts and over large volumes

- Proposal:
  - ~ 25,000 deg$^2$ survey
  - ~ 10,000 hours
  - To be done at the same time as the continuum and HI galaxy survey

- SKA1–Mid Band2: $0 < z < 0.5$
- SKA1–Mid Band1: $0.35 < z < 3$ (~1.45 with MeerKAT)
- SKA1–Sur Band2: $0 < z < 1.0$
- SKA1–Sur Band1: $0.6 < z < 3.0$ (without ASKAP dishes)
Problem: not enough short baselines (need ~ 20 m for BAO)

Solution: use each dish as a single telescope (auto-correlation)

“Like 254 GBT dishes but with less resolution”

Save the interferometer data (complement small scales)
The exciting stuff: Cosmology with a SKA1 HI intensity mapping survey

- Probe directly the gas (less sensitive to “peak statistics”)
- Detailed picture of the HI content of the Universe up to $z \sim 3$
- “Top of the game” constraints with BAO and RSDs (see talks from P. Bull and A. Raccanelli)
- Capable of probing BAO at very high $z$
- Capable of probing ultra–large scales (see talk by S. Camera)

Technical challenges: calibration

- Record signal as a function of time and frequency:
  \[ I \sim G^* (\text{Foregrounds} + \text{Signal}) + B + N \]
  - Gain: it fluctuates!
  - Instrumental effects
  - Noise term

- But we also have high resolution imaging with the interferometer for each pointing...

- Main idea: use the interferometer data to calibrate the gains

- Need to deal with correlated noise (1/f noise): survey strategy? (mapmaking techniques)

- Concerns with instrument stability...

- Note: we are not looking for an absolute signal: “long wavelength” fluctuations in frequency and angle are OK...
Important to test these auto-correlation techniques with data as soon as possible

First detection will also be important to “calibrate” $\Omega_{HI}$

Currently performing tests with KAT7 (a pathfinder for MeerKAT with 7 dishes, in South Africa).

More tests with WSRT, GMRT?
Galaxy (threshold) surveys:
- detect and count galaxies above a “safe” flux cut (~ 10 sigma)

Intensity mapping surveys:
- Need to remove everything else that falls in our pixel – foregrounds!

Major concern: polarisation leakage

Many statistical techniques to be explored!

HI intensity mapping: a great new window for cosmology with SKA1

It will allow SKA1 to provide “Euclid spectroscopy like” constraints for standard cosmology (but with different systematics)

Huge volume and high redshifts to probe ultra-large scales (signature of new physics, e.g. non-Gaussianity, GR corrections)

Challenges:
- SKA1 needs auto-correlations
- Calibration using interferometer
- Survey strategy to deal with correlated noise

But doable: low risk with high returns!
Go SKA!!
Go Portugal!!

Thank you!