Cosmology from HI galaxy surveys with the Square Kilometer Array

Radiometry Equation

\[
\text{snr} = \frac{1}{2} \frac{A_{\text{eff}} S [\tau \delta \nu]^{1/2}}{kT_{\text{sys}}} \quad \text{for each polarization}
\]

For SKA, \( \sigma_{\text{rms}} = \frac{100 \text{ mJy}}{[\tau \delta \nu]^{1/2}} \), two polarizations

Filipe B. Abdalla
On behalf of the Cosmology SWG
Cosmology: Concordance Model

Heavy elements 0.03%
Neutrinos 0.3%
Stars 0.5%
H + He gas 4%
Dark matter 20%
Dark Energy 75%

Outstanding questions:
• initial conditions (inflation?, $f_{nl}$)
• nature of the dark matter
• nature of the dark energy
• value of the neutrino mass

There are fluctuations at all scales but there is a preferred scale of around 1 deg.
What to look forward to:

- Three arrays in SKA1, SKA-Low, SKA-Mid and SKA-SUR, all of which can do some cosmology, with high specifications aside (~2019+):
- This baseline design can be very powerful if utilised properly.
- SKA2 will follow having close to the original presumed capabilities of the SKA.
21cm: a Hydrogen Detector

Higher energy state

Spin flip

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

SPECTRAL domain
0.5 to 1.4 GHz

local hydrogen

redshifted galaxy
modelling
SKADS sims

Millennium Simulation
(Springel et al. 05)
Dark matter

Semi-analytics
(De Lucia et al. 06/07)
Visible matter

Post-processing
(Obreschkow et al. 08)
Neutral atomic hydrogen

DM haloes, merger trees
SFR, cold gas mass
HI from cold gas mass
Full SKA1 and SKA2 Predictions
Have to rely on educated guesses

\[
\frac{M_{HI}(z)}{M_\odot} = 0.235 \frac{D_L^2(z) \, S_\nu \, V}{1 + z \, \text{Mpc}^2 \, \text{\nu Jy km/s}}
\]

Results from Santos et al. (HI simulations chapter)
Full SKA1 and SKA2 Predictions
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Results from Santos et al. (HI simulations chapter)
“Wavelength” of baryonic acoustic oscillations is determined by the comoving sound horizon at recombination:

\[ k_{bao} = \frac{2\pi}{s} \]

At early times can ignore dark energy, so comoving sound horizon is given by:

\[ s = \frac{1}{H_0\Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{eq})^{1/2}} \]

Sound speed (dependent on baryon/photon ratio) is only weakly dependent on epoch, and can be approximated by:

\[ c_s \approx \frac{0.9}{\sqrt{3}} c \]
BAO in LSS

\[ \delta r = D_A \delta \theta \quad \delta r = (c/H) \delta z \]

\[ H(z) = h \sqrt{\Omega_m (1+z)^3 + \Omega_X \exp \left[ 3 \int_0^z \frac{1 + w(z)}{1+z} dz \right]} \]

\[ D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)} \]

\[ r_\parallel = \frac{c \Delta z}{H(z)} \quad r_\perp = (1+z) D_A(z) \Delta \theta \]

\[ P_{\text{obs}}(k_{\text{ref} \perp}, k_{\text{ref} \parallel}) = \frac{D_A(z)^2_{\text{ref}} \times H(z)}{D_A(z)^2 \times H(z)_{\text{ref}}} P_{\text{true}}(k_\perp, k_\parallel) \]
SKA1 and SKA2 results on BAO

• Euclid will be the benchmark for cosmological experiments in the next decade.

• SKA1 will not be competitive with BAO Euclid in terms of galaxy survey but will be for SKA2.

• SKA1 will be complementary with Euclid as the redshift ranges are not completely overlapped.

Results from Bull (BAO chapter)

• Ross et al. 12

LG magnitudes:
- $i_{\text{mag}} < 18.5$
- $18.5 < i_{\text{mag}} < 19$
- $19 < i_{\text{mag}} < 19.3$
- $19.3 < i_{\text{mag}} < 19.6$
- $19.6 < i_{\text{mag}} < 19.9$

star magnitudes:
- $19 < i < 19.3$
- $19.3 < i < 19.6$
- $19.6 < i < 19.9$
- $19.9 < i < 20.1$
- $20.1 < i < 20.3$
- $20.3 < i < 20.5$

seeing < 0''.9
- 0''.9 < seeing < 1''
- 1'' < seeing < 1''1
- 1''1 < seeing < 1''2
- 1''2 < seeing < 1''3
- seeing > 1''3

LG magnitudes:
- $i_{\text{mag}} < 20.5$
- $20.5 < i_{\text{mag}} < 20.75$
- $20.75 < i_{\text{mag}} < 21$
- $21 < i_{\text{mag}} < 21.25$
- $21.25 < i_{\text{mag}} < 21.5$
- $i_{\text{mag}} > 21.5$
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• $w_0 - w_a$ vs. $k$ [Mpc$^{-1}$]
Galaxies act as test particles with the

$$ds^2 = -(1 + 2\psi)dt^2 + a^2(1 + 2\phi)dx^2$$

If fact, we can expect a small peak velocity-bias due to motion of peaks in Gaussian random fields.

$$k^2\psi = k^2\phi = -4\pi G a^2 \rho_m \delta$$

On large-scales, the distribution of galaxy velocities is unbiased provided that the positions of galaxies fully sample the velocity field.

$$\delta'' + \frac{3}{2}a^{-1} \left[ 1 - w(a) \left( 1 - \Omega_m(a) \right) \right] \delta' - \frac{3}{2}a^{-2}\Omega_m(a)\delta = 0 ,$$
assume: irrotational velocity field due to structure growth, plane-parallel approximation, linear deterministic density & velocity bias, first order in $\delta, \theta$

\[
\delta_{\text{gal}}(k, \mu) = b\delta_{\text{mass}} + \mu^2 b_v \theta_{\text{mass}}
\]
\[
\delta_{\text{gal}}(k, \mu) = b\delta_{\text{mass}}(1 + \mu^2 b_v \beta)^2
\]
\[
\delta_{\text{gal}}(k, \mu) = \delta_{\text{mass}}(b + \mu^2 b_v f)^2
\]

Standard assumption: $b_v = 1$ (current simulations limit this to a 10% effect).

\[
f \equiv \frac{d \log G}{d \log a}
\]
\[
f \sigma_8 \propto \frac{dG}{d \log a}
\]
\[
G = \frac{\delta(z, \text{mass})}{\delta(0, \text{mass})}
\]

Normalise RSD to $\sigma_v$
Normalise RSD to $\beta = f/b$
Normalise RSD to $f \sigma_8$

Model is $\Lambda$CDM with $\Omega_m = 0.30$, $\sigma_8 = 0.80$

Expected errors for current / future surveys

RSD results for SKA (red) and Euclid (blue)

Full distortion results, AP, BAO, RSD

Results from Bull (RSD chapter)
Growth and Power Spectrum of density fluctuations

Field of density fluctuations
\[ \delta(x) = \frac{\delta \rho(x)}{\rho} \]

Fourier transform
\[ \delta(k) = \int d^3x \ e^{-ik \cdot x} \delta(x) \]

Power spectrum essentially square of Fourier transform
\[ \langle \delta(k) \delta(k') \rangle = (2\pi)^3 \delta(k-k') P(k) \]
with \( \delta \) the delta function

Power spectrum is Fourier transform of two-point correlation function
\[ \xi(x) = \langle \delta(x_2) \delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik \cdot x} P(k) \]
where \( x = x_2 - x_1 \)

\[
\begin{align*}
 ds^2 &= -(1 + 2\psi) dt^2 + a^2(1 + 2\phi) dx^2 \\
 \delta G_{\nu \mu} &= \frac{8\pi G}{c^4} \delta T_{\nu \mu} \\
 \frac{\partial^2 \delta}{\partial t^2} + 2H \frac{\partial \delta}{\partial t} &= \left( \frac{c_s}{a} \right)^2 \nabla^2 \delta + 4\pi G \rho \delta
\end{align*}
\]
Primordial Non-Gaussianity

- The non-Gaussian properties of initial fluctuations also lead to scale-dependent biasing and distinctive signatures on very large scales

\[ \Phi = \phi + f_{NL} \ast (\phi^2 - \langle \phi^2 \rangle) \]

- Local-type primordial non-Gaussianity

\[ \Delta b_X(k, z) = 3 \left[ b_X^{(G)}(z) - 1 \right] \frac{\Omega_m H_0^2 \delta_c}{c^2 k^2 T(k) D_+(z)} f_{NL} \]

[Dalal et al., 2008; Matarrese & Verde, 2008]
• Forecast constraints on $f_{NL}$ from SKA HI threshold surveys with different sensitivities and taking into account general relativistic corrections occurring on the largest scales.
Lowest neutrino mass allowed: ~0.05 eV and potentially the hierarchy

- LSS cannot measure a mass of 0.05 eV
- However LSS + CMB experiments can
- For such small masses N_nu is unconstrained
- However, if the mass is so small we have detected a normal hierarchy
- A combination of both can constrain N_nu to a certain extent.
Photo-z calibration: direct and cross correlation

- A spectroscopic survey to further calibrate photo-z or continuum surveys.
- Would, possibly, calibrate deeper photo-z surveys. See sims (Matthews and Davis 10).
  - Problem: degenerate with bias(z)
  - Problem: degenerate with Cosmology to a certain extent.
- Technique not put to the test on data yet! Would be nice to see it actually working. If so, SKA1 deep field and SKA2 could calibrate a large fraction of surveys such as LSST.
- McQuinn and White have optimized estimators
Photo-z calibration cross correlation: can we use RSD/CMB.

Thomas, Abdalla & Lahav 11a,11b
Cross correlations with SKA LSS surveys.

- HI threshold surveys will yield very pristine galaxy samples, with few/ different systematic effects compared to optical samples and IM data.
- Cross correlations with other datasets would infer systematic effects such as:
  - Bias of galaxies from samples
  - Redshift distribution of other samples such as photo-z samples and continuum surveys
  - Calibrate shear calibrations from lensing
- Cross correlation data will also provide improvements over other surveys such as:
  - Improved modified gravity constraints
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Results from Benoît-Levi (cross correlations chapter)
\[ ds^2 = -(1 + 2\psi)dt^2 + a^2(1 + 2\phi)dx^2 \]

Two perturbation/metric potentials in the ‘Newtonian Gauge’

N.B - Modified Gravity might break the relationship between potential powerspectrum and the matter powerspectrum

**LSS RSD and BAO**

\[ \Delta^2(k) \equiv \frac{4\pi k^3 P(k)}{(2\pi)^3} \]

\[ <\delta(k, z)\delta(k', z)> = (2\pi)^3\delta_D(k + k')P_\delta(k, z) \]

\[ C_\ell \equiv <\delta^{2D}\delta^{*2D}> = 4\pi \int \Delta^2(k)W_i(k)W_j\frac{dk}{k} \]

**WL**

\[ P_\kappa(l) = \frac{9H_0^4\Omega_m^2}{4c^4} \int_0^{\chi_H} \left[ \frac{g(\chi)}{a(\chi)} \right]^2 P_\delta \left( \frac{l}{\chi}, \chi \right) d\chi \]

**Deflection Angle**

\[ \alpha = -\int \partial(\psi + \phi)ds \]

**GR**

\[ \dot{\delta} + 2H\dot{\delta} = -\frac{k^2}{a^2}\psi \]

\[ k^2\phi = -4\pi Ga^2\rho_m\delta \]

\[ P_\phi(k, z) = (4\pi G)^2a^4\rho^2\frac{P_\delta(k, z)}{k^4} \]

**MG**

\[ \psi \equiv [1 + \eta(k, a)]\phi \]

\[ k^2\phi \equiv -4\pi Ga^2Q(k, a)\rho_m\delta_m \]

\[ P_{\phi+\psi}(k, z) = (4\pi G)^2a^4\rho^2[Q(1 + \eta/2)]^2\frac{P_\delta(k, z)}{k^4} \]
SKA 1 and SKA 2 testing DE and MG at large scales

- Measurements of the comparison between the two potentials is possible
- All results include full calibration of the photo-z in WL from the spectroscopic cross correlation
- SKA1 and SKA2 will be better than Euclid given their large number of galaxies at low z
- All results include a Planck prior...
- All large scale cross correlations calibrate the photo z with an accuracy in the per cent level...
  Further small scale deep surveys can calibrate further (not added here)

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Results from Kirk (cross correlations chapter)
• PCA are best measured by SKA type surveys. Shown in Tang et al. 08 and in Zhao et al. (14)

• Principal components analysis for MG calculated in Zhao et al. (2014). Still large number of PCs measured by Ska type surveys whereas.
Conclusions

• The SKA1 and SKA2 will be competitive with HI galaxy surveys. Several highlights: BAO, RSD, fnl, cross-correlations, MG.

• Despite the much reduced capabilities for SKA1 many areas remains competitive even with surveys such as Euclid, including:
  – Redshift space distortions at low redshift
  – Cross correlations and redshift calibration
  – Cross correlations for MG estimation
  – Modified gravity constraints including PCA analysis