COSMOLOGY WITH THE SKA

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HUGE GALAXY SURVEYS – THE NEXT FRONTIER

State-of-the-art galaxy surveys today (BOSS, DES)

The next generation of surveys – SKA, Euclid, LSST, ... – will deliver much greater volume and thus precision.
SKA Phase 1

2 sites (South Africa, Australia);
3 telescopes; one Observatory
Frequency range SKA1: 50 MHz – 3 GHz

Cost-cap: €650M
Construction: 2017 – 2023
Early science: 2020
Phase 2 SKA: 2023 - 2030

SKA-Mid: ~ 190 15m dishes + MeerKAT, RSA

SKA-Low: ~ 250,000 low-freq dipoles, AUS

SKA-Survey: ~ 60 15m dishes + ASKAP, AUS

Exploring the Universe with the world’s largest radio telescope
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133 dishes
by 2017

SKA-Low: ~ 250,000 low-freq dipoles, AUS
125,000

SKA-Survey: ~ 60 15m dishes + ASKAP, AUS
0 – deferred
2 of the 64 MeerKAT dishes
COSMOLOGICAL SURVEYS IN THE RADIO

HI GALAXY REDSHIFT SURVEY

- Neutral Hydrogen emits 21cm/ 1420 MHz in restframe
- Individual HI galaxies detected, very accurate redshifts
- The radio analogue of an optical spectroscopic survey
- No foregrounds, no stellar contamination
- But – this needs very high sensitivity

[Image of intensity mapping after reionisation]
HI INTENSITY MAPPING SURVEY

- Individual HI galaxies **not** detected, only integrated HI emission
- Perfectly good for large-scale cosmology (BAO, RSD, PNG)
- Very narrow redshift bins possible
- Like the CMB – but at many redshifts
- Mainly via single-dish auto-correlations
- Major problem of foreground removal (worsens as $z$ increases)
- Also used in Epoch of Reionization experiments
COSMOLOGICAL SURVEYS IN THE RADIO

RADIO CONTINUUM SURVEY

- Total radio emission from galaxies (mainly synchrotron)
- No redshift information – but can get some, using HI or optical data
- Many galaxies at high redshift
SOME OF THE BIG QUESTIONS

• Is Dark Energy not the vacuum energy $\Lambda$ – but a dynamical field?
  
  \[ w \equiv \frac{p_{de}}{\rho_{de}} = w_0 + (1 - a)w_a \]

• Is there no DE? Is acceleration driven by modified gravity? i.e. – does GR fail on the largest cosmological scales?

• Is the primordial spectrum of perturbations non-Gaussian? What does it tell us about Inflation?

• Is the large-scale structure of matter isotropic like the CMB?

Probes that we use to answer these questions:

BAO + redshift space distortions + angular power spectra
BAO – a fossil record in the galaxy distribution

galaxy formation
$z < 30$

decoupling
$z = 1100$
BAO – a powerful probe of $H(z)$ and $D_A(z)$

Measure $\Delta \theta(z)$ and $\Delta z$

Deduce $D_A(z)$ and $H(z)$

\[
\frac{r_s}{1 + z} = D_A(z) \Delta \theta(z) \\
\frac{r_s}{1 + z} = \frac{\Delta z}{(1 + z) H(z)}
\]

$r_s \approx 100 h^{-1}$ Mpc
CMB

Galaxy correlations
Redshift space distortions

The average motion of galaxies relative to us is given by the Hubble expansion.

Over-dense regions (e.g., galaxy clusters) and under-dense regions (e.g., voids) induce additional peculiar velocities relative to the Hubble flow.
The Kaiser formula

\[ \delta_{g \text{obs}} = (b + f \mu^2) \delta_m \]

where

\[ \mu = \mathbf{n} \cdot \hat{\mathbf{k}} = \frac{k_\parallel}{k} = \cos \alpha \]

leading to the power spectrum:

\[ P_{g \text{obs}}(\eta, k, \mu) = (b + f \mu^2)^2 P_m(\eta, k) \]
Measuring the monopole and quadrupole allow us to separately extract $b$ and $f$ (up to a normalization of the power spectrum).

The growth rate $f$ is a good diagnostic of deviations from LCDM and also from GR.

Parametrization:

$$f(\eta, k) = \left[ \Omega_m(\eta) \right]^{\gamma(\eta, k)}$$

In LCDM, and dynamical DE where the clustering of DE is negligible,

$$\gamma \approx 0.55$$

A significant deviation from this value could indicate a breakdown of GR.
SKA COSMOLOGICAL SURVEYS

HI GALAXY REDSHIFT SURVEY

- SKA1 – 10 million galaxies, 5000 deg$^2$, $z<0.6$
- SKA2 – 1 billion galaxies, 30000 deg$^2$, $z<2$

SKA1 will not be a game-changer but will provide excellent complement to optical surveys

SKA2 will be a game-changer

(Yahya et al 2015)
SKA COSMOLOGICAL SURVEYS

HI INTENSITY MAPPING SURVEY
SKA1 – 30000 deg², z<3

Wide area and deep redshift – can measure very large scales with game-changing precision.

Error over signal on P(k) at k~0.01/Mpc – beyond turnover scale

(Bull et al 2015)
Huge volume of SKA1 intensity mapping
Volume of different surveys

(Maartens et al 2014)
Redshift reach of spectroscopic SKA and optical/IR
SKA COSMOLOGICAL SURVEYS

CONTINUUM SURVEY

- SKA1 – 100 million galaxies, 30000 deg²
- SKA2 – 2 billion galaxies, 30000 deg²

Key advantages of radio continuum and HI surveys:
- more independent modes than optical/IR/CMB
- different systematics from optical/IR
Consistency between galaxies & CMB

In standard cosmology, the dipole of the matter distribution should agree with the dipole of the CMB.

NVSS all-sky radio survey shows consistency in direction (within very large error bars) but not amplitude.

SKA angular correlation function (100's millions galaxies) will be able to detect dipole within $\sim 5^\circ$ (Phase 1) and $\sim 1^\circ$ (Phase 2).
BAO precision – radial

\[ \frac{\sigma_H}{H} \]

- BOSS forecast (GS)
- H\alpha survey (GS)
- HETDEX (GS)
- SKA2 (GS)
- MID B2 + MK (GS)
- MID B1 + MK (IM)
- MID B2 + MK (IM)
- LOW (IM)

Bull 2015
BAO precision – transverse

$\frac{\sigma_{DA}}{DA}$ vs $z$

- BOSS forecast (GS)
- $H\alpha$ survey (GS)
- HETDEX (GS)
- SKA2 (GS)
- MID B2 + MK (GS)
- MID B1 + MK (IM)
- MID B2 + MK (IM)
- LOW (IM)

Bull 2015
Probing Dark Energy using RSD

Bull 2015
Testing General Relativity using RSD

Bull 2015
Observed galaxy counts on the largest scales

We count the number of galaxies per pixel:

\[ N(n, z) \, d\Omega \, dn \, dz \]

How do we describe the count fluctuations theoretically?
We need the correct bias definition (in synchronous gauge) plus RSD:

$$\delta_{\text{obs}} = b \Delta_m - \frac{1}{\mathcal{H}} \partial_x (\mathbf{n} \cdot \mathbf{v}_m)$$

There are additional terms from redshift perturbations and volume perturbations. Start with **lensing**:

Distant galaxies are magnified by intervening matter. The number density of lensed galaxies is related to the unlensed number density by

$$n_g = \frac{\bar{n}_g}{\mu} \approx \bar{n}_g (1 - 2\kappa)$$

where we neglect magnification bias and the lensing convergence is

$$\kappa = -\frac{1}{2} \nabla^2 n \int_{\eta_0}^{\eta} d\tilde{\eta} \frac{(\tilde{\eta} - \eta)}{(\eta_0 - \eta)(\eta_0 - \tilde{\eta})} (\Phi + \Psi).$$
This leads to a lensing contribution to the number counts:

\[ \delta_{\text{obs}} = b \Delta_m - \frac{1}{\mathcal{H}} \partial \chi (n \cdot v_m) - 2\kappa \]

- RSD allow us to effectively measure peculiar velocities
- Lensing convergence allows us to effectively measure the lensing potential from number counts (Alonso et al 2015, Montanari & Durrer 2015)

This offers a possible new way to measure the lensing potential – without the need to measure shapes or sizes or magnitudes of galaxies.
What other contributions are there to $\delta_{\text{obs}}$?

Gravitational redshift?

Thinking of the CMB – what about Sachs-Wolfe and ISW effects? And time-delay?

These (and some other terms) are all present – but they are only non-negligible on horizon scales.
We need to consider the full perturbed lightray equation, including the perturbation of the direction vector.

These effects have been computed:

Yoo, Fitzpatrick, Zaldarriaga 2009; Yoo 2010; Bonvin, Durrer 2011; Challinor, Lewis 2011
Notation change: \( \delta_{\text{obs}} \rightarrow \Delta, \quad \Delta_m \rightarrow D, \quad \chi \rightarrow r, \)
New information in the observed overdensity. Relativistic terms grow on very large scales – but there is **cosmic variance**.
Primordial non-Gaussianity in the galaxy distribution

- Primordial quantum fluctuations generated during Inflation – may be non-Gaussian.
- Primordial non-Gaussianity is ‘frozen’ on large scales during the expansion of the Universe.
- The effect of PNG of local type is to modify the bias of galaxies relative to the underlying total matter distribution:

\[ \Delta_g = b \Delta_m \text{ where } b \rightarrow b + \Delta b, \quad \Delta b \propto f_{NL} k^{-2} \]

Local PNG thus boosts the clustering of galaxies on very large scales.
The same problem of cosmic variance.
And – degeneracy between GR effects and PNG
Cosmic variance limits our ability to
- Measure the horizon-scale GR effects
- Measure PNG at the level \( \sigma(f_{NL}) < 1 \)

Even the biggest and best future galaxy surveys – Euclid and SKA – will be unable to measure these effects on their own.

However, with the multi-tracer method – i.e. using 2 different tracers of the matter stochastic DM distribution – we can detect the horizon-scale GR terms at high confidence, and achieve \( \sigma(f_{NL}) < 1 \)

(Alonso & Ferreira 2015, Fonseca et al 2015)
Multi-tracer method – using SKA1 HI intensity mapping + Euclid photometric survey

- New information from the galaxy distribution on horizon scales
- Probe PNG well beyond the CMB precision – new tests of inflation
THE HEADLINE MESSAGE

SKA1
• HI intensity mapping survey:
  precise BAO, RSD up to z~3
  excellent constraints on DE and modified gravity
  probe the largest scales ever – non-Gaussianity, modified gravity
• HI galaxy redshift survey:
  precise RSD at z<0.5
• Continuum survey:
  test isotropy of the universe
  good constraints on non-Gaussianity

SKA2
• HI redshift survey (‘billion galaxy survey’) will be the state of the art
• Radio lensing competitive with optical lensing surveys

SYNERGY
• Radio gives different systematics to optical/ IR – and the combination
  is stronger than each separately