New Probes of Old Structure: 21cm Intensity Mapping and the Cosmic Microwave Background

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We’re storytellers, and what could be more grand than the story of creation?

- Brian Greene
A Brief History of the Universe

Big Bang Expansion
13.77 billion years

1st Stars
about 400 million yrs.

Development of
Galaxies, Planets, etc.

Dark Ages

Dark Energy
Accelerated Expansion

Afterglow Light Pattern
375,000 yrs.
A Brief History of the Universe

WMAP/NASA
That seems neat and tidy, but …
“If you cannot measure it, you cannot improve it” - Kelvin
Stacking new ACTPol 'deep56' temperature map on hot spots. From Zhiqi Huang and Dick Bond.

TEMPERATURE: Stack where SNR >1.

Same fundamental scale

Artist impression

Credit: Huang & Bond
Acoustic oscillations in the hot, dense Universe

at $t < 380,000$ years

Baryon Density

Photon Density

Radial Profile

Credit: M White
Acoustic oscillations in the hot, dense Universe

t *still* less than $380,000$ years

Baryon Density

Photon Density

Radial Profile

Credit: M White
Acoustic oscillations in the neutral Universe

$t \approx 380,000$ years

Baryon Density

Photon Density

Radial Profile

Credit: M White
Acoustic oscillations in the neutral Universe

t > 380,000 years

Baryon Density

Photon Density

Radial Profile

Credit: M White
Acoustic oscillations in the neutral Universe

t > 380,000 years

Baryon Density

Photon Density

Radial Profile

Credit: M White
Acoustic oscillations in the neutral Universe

Now

regular matter ends up here

Baryon Density

Photon Density

Radial Profile

Credit: M White
Large Scale Structure Distribution

~300,000 Galaxies trace the distribution of Large Scale Structure
Sanchez et al, 2012

Correlation function
Anderson et al 2013b
BOSS survey
Cosmic Microwave Background

Credit: Huang & Bond
Standard Ruler

Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago
Baryon Acoustic Oscillations (BAO)

Anderson et al 2013b
BOSS survey

Anderson et al 2013b
BOSS survey

'Radius'
What do we measure when we measure Dark Energy?

\[ P = w \rho \] (equation of state)

\[ \rho = a^{-3(1+w)} \] (Use Einstein General Relativity + FRW)

Scale factor: encodes cosmic size relative to today (a=1 today)
What do we measure when we measure Dark Energy?

\[ \rho = a^{-3(1+w)} \]

\[ P = w \rho \]

(equation of state)

relativistic gas: \( w = 1/3 \)

\( w = 0 \)

\( \Lambda(\rho \sim \text{const}) \)
What do we measure when we measure Dark Energy?

\[ \rho = a^{-3(1+w)} \]

\[ P = w\rho \]

(equation of state)

Best constraints show:

\[ w \sim -1 \]
“If you cannot measure it, you cannot improve it” - Kelvin

\[ \rho = a^{-3(1+w)} \]

\[ P = w\rho \]

(equation of state)

Best constraint so far:

\[ w = -1.06 \pm 0.07 \]  

(a \sim 0.6)
How are we doing so far?

Cosmological Distance

\[
\frac{D_V}{r_s}/(D_V/r_s)_{\text{fid}}
\]

t~14 Gyr (now)  t~6 Gyr  t~3 Gyr

Dark Energy dynamically important

6dFGS  BOSS  WiggleZ  SDSS-II

BOSS Ly-α
The scale of interest is *Large*...

150 Mpc radius

Sanchez et al, 2012
So we don’t need to resolve individual galaxies.

DO need:
- Traces (dark) matter distribution
- Redshift information (time)

~(CHIME resolution)

150 Mpc radius
Hydrogen Intensity Mapping

Same Galaxy — Neutral Hydrogen in un-ionized bubbles, supported within galaxies
What do I build?

- redshift: $z = 0.8$, $t = 3 \text{ Gyr}$
- redshift: $z = 2.5$, $t = 7 \text{ Gyr}$
- redshift: $z = 0$, $t = 14 \text{ Gyr}$

Radio astronomy

21cm

75cm (400 MHz)

38cm (800 MHz)
The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

- 4 cylinders: 20m x 100m
- 1024 dual-polarization feeds
- 400-800MHz
- Constructed, instrumented this year
The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

Credit: Peter Klages
If you’re going to try cross-country skiing, start with a small country.

- (Anonymous)
CHIME Pathfinder

• Pathfinder is a test-bed
  • 2 shorter cylinders (20m x 40m)
  • 128 dual-pol feeds
  • See Bandura et al 2014 (arXiv 1406.2288) for more instrument details
• Fielded and taking data!
Front End: Feeds

Deng et al, 2014
Front End: Low Noise Amplifiers

Figure 10: LNA gain and noise measurements.

(a) In band
(b) Broadband

Figure 11: First stage LNA S parameter measurements
Front End: Filter Amplifiers

Shipping container
Back End: Graphics Processing Units

Full CHIME: $x \times 8 \times 13\text{Tb/s}$

Total global cell traffic: $\sim 6\text{Tb/s}$ (2014 Cisco)

Pathfinder GPU correlator

(x 128 for full CHIME!!!
(will rank in the Top 10 computers)
Preliminary map

x 1024 frequencies x 2 years

(659-659.4 MHz)

Credit: Richard Shaw
Preliminary map

Simulated observation

Credit: Richard Shaw
Current state-of-the-art

Cosmological Distance

\( \frac{D_V}{r_s} \)/\( \frac{D_V}{r_s} \)_{\text{fid}}

Now

Time

Dark Energy dynamically important

BOSS Ly-\( \alpha \)

BOSS

WiggleZ

6dFGS

SDSS-II
Current state-of-the-art

Cosmological Distance vs. Time

- BOSS
- 6dFGS
- WiggleZ
- SDSS-II
- Full CHIME
- BOSS Ly-α
- CHIME pathfinder

Dark Energy dynamically important
We have some problems challenges...
We have some problems challenges…

Require: <1% gain error
<0.1% beam error

{ Shaw et al 1401.2095
LBN et al, 2014 }
We have some problems challenges...

Require: \(<1\%\) gain error
\(<0.1\%\) beam error

Shaw et al 1401.2095

Simulated Sky

LBN et al, 2014
Why Do We Have to Know the Beams?
The reason this is hard...
Calibrate with Holography

Correlate (in Pathfinder correlator)

Tracking dish

Transiting source
Holographic beam scans from CygA

Analysis by grad student Phil Berger
What does this look like?

Beam

Pulsar tracks

Simulations by grad student Liam Connor
What does this look like?

Beam

Pulsar tracks

Simulations by grad student Liam Connor

Actually mapping the NS beam .... Drones! (also maybe a Cesna)
Hydrogen Intensity and Real-time Analysis Experiment (HIRAX)
HIRAX

(3x collecting area of CHIME)

- 1024 6m dishes
- 400—800MHz
(you may ask: why dishes?)

Site: Karoo Desert
(funded by South Africa)
HIRAX: 8-dish prototype

Prototype dish #1 —- on roof of UKZN, SA

Going down in March!
to deploy test focus modules
I’ve been talking a lot about BAO:

- **Galaxy Survey**
- **CHIME Survey**
Effect from Lensing

$17^\circ \times 17^\circ$

lensing potential

unlensed cmb

Credit: Alex van Engelen
Effect from Lensing

$17^\circ \times 17^\circ$

lensing potential

lensed cmb

Credit: Alex van Engelen
Probing Large Scale Structure with ACTPol
Probing Large Scale Structure with ACTPol

Graduate students
Emily Grace and
Christine Pappas
& Prof. Suzanne Staggs

~1000 detectors
150 GHz
100 mK
Probing Large Scale Structure with ACTPol

Power spectrum
(Naess et al, 2014)

Lensing detection
(Van Engelen et al, 2014)

Dark Matter Halo lensing
(Madhavacheril et al 2015)

Radio galaxy LSS
(Allison et al 2015)

Probing growth rate of Structure
(Schaan et al 2015)

Photon’s eye-view of ACTPol
Probing Large Scale Structure with ACTPol

Power spectrum
(Naess et al, 2014)

Lensing detection
(Van Engelen et al, 2014)

Dark Matter Halo lensing
(Madhavacheril et al 2015)

Radio galaxy LSS
(Allison et al 2015)

Probing growth rate of Structure
(Schaan et al 2015)

From stacking on SDSS / BOSS galaxy survey

From correlation with NVSS radio data

Using analysis with SDSS / BOSS galaxy survey
Wide Survey overlap

**Advanced ACTPol Survey:**
20,000 square degrees, complete overlap with LSST

**Survey Plans**

**DESI:** 2018 — 2022
- 25 million galaxies
  - $z < 2$
- 300 million galaxies
  - $z < 1.4$

**LSST:** 2020 — 2030
- ~billions galaxies
  - $z < 3$

**DES:** Aug 2013 +5 years
- 300 million galaxies
  - $z < 1.4$
Wide Survey overlap

Advanced ACTPol Survey:
20,000 square degrees, complete overlap with LSST

Different probes, different systematics
Also with LSS:
- isotropy
- $f_{NL}$
- $\Sigma m_\nu$
- modified GR $\leftrightarrow$ Dark Energy
- ...
Also with LSS:

- isotropy
- $f_{NL}$
- $\sum m_{\nu}$
- modified GR $\leftrightarrow$ Dark Energy
- ...
CHIME: A 21cm Stage 4 Dark Energy Experiment

allowed region: Planck++
expected allowed region: Planck++ CHIME

\[ w(z) = w_0 + w_a \left( \frac{z}{z+1} \right) \]
When to measure?

- BOSS
- 6dFGS
- WiggleZ
- SDSS-II
- BOSS Ly-α
- CHIME pathfinder
- Full CHIME

Cosmological Distance

Dark Energy dynamically important

Now

Time
A Fast Fourier Transform Interferometer

‘FFT Telescope’:

Regular correlation: $\sim N^2$
DFFT correlation: $\sim N \log N$

(Tegmark and Zalarriaga, 2008)
Can remove them!

Shaw et al 1401.2095

Power spectrum errors (400-500MHz)
(As long as we know our instrument)

Shaw et al 1401.2095

Complex Gain Error
(As long as we know our instrument)

Shaw et al 1401.2095

Beam Error
Foreground Removal?

• Foregrounds are highly correlated
  • Can change basis into one where that is more apparent with the Karhunun-Loeve transform
  • But, this requires covariance matrices:
Solution: M-Modes

- Data has periodicity in sky angle ($\phi$), encouraging an additional spherical harmonic: $m$ (Shaw et al 1302.0327 & 1401.2095)

- M-modes are statistically independent
CHIME Forecasts

• Can do science with the pathfinder
• Full CHIME breaking ground this summer, anticipate 5 years of data
• 0.52 - 0.26 deg beamsize (400-800MHz)
• 10 - 45 Mpc resolution (400-800)
• 50K, 2K/Jy, 1.5uJy/pixel final sensitivity (50uJy/pixel daily),

Planck + current experiments
Planck + current + CHIME (simulations)

$2 \sigma$ contours

$w_0$

$D_H(z)/H_0$

$\Delta D_M(z)/100\text{Mpc}$

$\Delta H(z)/H_0$

Redshift $z$
CHIME Forecasts

- WiggleZ: $1.2 \ (h^{-1} \ Gpc)^3$
- BOSS LRG: $5.3 \ (h^{-1} \ Gpc)^3$
- LyA: $37 \ (h^{-1} \ Gpc)^3$
- CHIME: $203 \ (h^{-1} \ Gpc)^3$ (scaled such that area of patch = volume of survey)

Survey Volume

- DE dynamically important

- Volume limited
- Angular resolution limited

Simulations

- Spectrum with BAO
- Spectrum w/out BAO

Anticipated sensitivity for two years of data (projected to a single redshift $z=1.5$)
Calibration: Gain and Phase

Noise injection setup

Antennas

- A copy of the noise injection signal is sent to a broadcasting linear polarization antenna installed at the north end of the cylinders.
- It is possible to achieve a relatively flat illumination of the CHIME feeds by pointing the broadcasting antenna to the furthest feed.

Noise Rigidization
Baryon Acoustic Oscillations: 3D map

(geometry)
- test of isotropy
- test of expansion

(growth)
- Dark Energy vs modified General Relativity
- total neutrino mass

Resulting 3D map of structure an enormously powerful probe of cosmology:
Pulsar Timing Arrays

**Pulsar Timing**
- Primordial gravitational waves
- Inflation

**ELF**
- CMB

**VLF**
- Supermassive Black Hole Binaries
- Cosmic strings

**Space-based interferometers**
- Stellar mass compact binaries
- Massive black hole mergers

**Ground-based interferometers**
- Neutron star binaries
- Black hole binaries

**Frequency [Hz]**

![Image of a pulsar with emitting beams]
Pulsar Timing Arrays

Pulsar B0329 in CHIME pathfinder data

Credit: Liam Connor
Beamforming

Single feed, single dish beam shape

$2^\circ$
Digitally add delays to mimic pointing

"Beam forming"
Full CHIME

1280 dual-pol feeds

FFT / Beamforming Correlator

1280 dual-pol beams

Resolution: 15-30'

Requires the ability to ‘calibrate’: know the delays to add in real time
Calibration: Beams

- Any given beam is large
- Can get transit data for about four sources: CasA, CygA, TauA, M87
- Required 0.1% calibration is off the table with this method
21cm Cosmology is not just CHIME

- ‘Epoch of Reionization”
  - measure neutral hydrogen at very high redshift
  - first galaxies
  - this is the primary science goal for many different experiments: EDGES, PAPER, MWA, GBT, GMRT, etc
  - It is in the set of science goals for SKA

CHIME frequency range isn’t even on this plot!
approximately 20 was still running after two days and we manually stopped it. Optimization of s11. Altering learn which parameters have the most impact on the antenna's using a mechanical jig. A photo of eight antennas in a linear PCB pieces of the cloverleaf antenna are soldered together HPBW varies within several degrees across the band. The six beam pattern is smooth in both the E-plane and the H-plane. in comparison with simulations. According to simulation, the Note that the resulting petal size and shape are compatible serious effect on both antenna impedance and material losses. FR4. The circuit boards are slotted to remove FR4 in the gaps between petals because leaving FR4 in the gaps has a FR4. We used the optimization algorithm implemented in CST to successively, to two segments with different impedances. From among \( W, L = 138 \) mm and altered \( f = 580 \) MHz, \( L = 150 \) mm which has the smallest s11 across \( f \). We stopped our tuning procedure at this point. Although \( R, W, L \) has very little impact, and we fixed it to \( W, L = 20 \) mm and \( R = 5 \) W, L \( = 131 \) mm and altered \( W \), L \( = 12 \) dB. From this result and \( (R, W, L = 138, W, L = 150) \) to \( (R, W, L = 138, W, L = 150) \) \( \leq 10\)dB. From this result and \( (R, W, L = 138, W, L = 150) \) \( \leq 10\)dB. From this result and

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\begin{align*}
S_{11} & = \frac{1}{1 + \frac{f^2}{f_0^2}} \\
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CHIME Projections

Simulations

large scales

small scales

CHIME averaged to z=1.5

volume limited

angular resolution limited

Spectrum with BAO
Spectrum w/o BAO

Spectrum with BAO
Spectrum w/o BAO
Transient Science

- We will make daily maps of ~3/4 of the sky. This leads to a variety of auxiliary science goals:
  - pulsars: dispersion measures for pulsar timing (~300 pulsars)
  - bursts for LIGO coincidence searching
  - SN1a progenitors in radio
  - Fast Radio Bursts
  - …
It’s a statistical statement

Credit: A. Hincks
It’s a statistical statement

Credit: A. Hincks
Nonlinear corrections are around 10^2, causing the power spectrum to have little power there. The typical wavelength scale is 100 Hubble radii. Larger wavelengths coherently move both galaxies while smaller wavelengths contribute to the sharpness of the correlation function bump. The width of the correlation function bump corresponds to the characteristic BAO scale, as shown in Figure 1.16. This setup makes the detection of BAOs harder.

Various methods can be followed to reconstruct the velocity field, which can then be used to undo the effect of successively broadening rings from the peak of the correlation function. This velocity field can then be used to map the velocity of the universe back to its standard ruler length.

Recent studies have shown that the map of galaxies used to extract the power spectrum in redshift space can also be used to reconstruct the standard ruler length more noisy. In addition, the width of the correlation function bump provides information about the characteristic BAO scale. The sharpness of the correlation function bump is important for accurately measuring the universe's expansion rate and for understanding the dynamics of the universe. The characteristic BAO scale is a sensitive probe of the universe's geometry and can provide insights into the nature of dark energy and dark matter.
What do I build?

- Requires highest sensitivity, highest telescope resolution
- Sources fainter, BAO smaller

- NOW
  - redshift: $z = 0.8$
  - t = 3 Gyr

- t = 7 Gyr
  - redshift: $z = 2.5$

- t = 14 Gyr
What do I build?

Signal level: $\sim 100\mu K$, need:
1) $\sim 1000$ detectors
2) a lot of collecting area
3) low noise

Resolution $\sim \lambda / D \rightarrow 80$ m dish!

75 cm

50 Mpc $\leftrightarrow \sim 0.5$ degrees

redshift: $z = 0.8$

redshift: $z = 2.5$

t = 7 Gyr

t = 3 Gyr

NOW

t = 14 Gyr

NOW
Back End: FPGA Frequency Channelizer

Full CHIME: \( x \ 8 \ : \ 13\text{Tb}/s \)

Total global cell traffic: 
\(~6\text{Tb}/s\) (2014 Cisco)

output: 1024 frequencies per sky input
Back End: Graphics Processing Units

x 128 for full CHIME!!!
(will rank in the Top 10 computers)

Pathfinder GPU correlator
But there was another spectrum...

Credit: Huang & Bond

Large Scales

Small Scales

Naess et al 2014
ACTPol

Planck
ACT 2013
ACTPol

None
None
None

$D_\ell [\mu K^2]$

Angular scale

Multipole $\ell$

$180^\circ$ $1^\circ$ $0.2^\circ$ $0.1^\circ$ $0.04^\circ$ $0.02^\circ$

$10^3$

$10^2$

$10^1$

$10^0$

$218\times218$ GHz

$148\times218$ GHz

$148\times148$ GHz

Polarized sources [no masking]

SZ+CIB+Radio

Credit: Huang & Bond

TEMPERATURE: Stack where SNR > 1.

Zhiqi Huang and Dick Bond.
Redshift desert

\[ \frac{D_v}{r_s} / \left( \frac{D_v}{r_s}_{\text{fid}} \right) \]

\( z \)

Dark Energy dynamically important

38 cm = 800 MHz

75 cm = 400 MHz

BOSS
6dFGS
WiggleZ
SDSS-II
BOSS Ly-\( \alpha \)

Full CHIME pathfinder