“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)
Baryon Acoustic Oscillations (BAO) Standard Ruler
BAO from galaxy surveys

~300,000 Galaxies trace the distribution of Large Scale Structure

Correlation function

Anderson et al 2013b
BOSS survey

Sanchez et al, 2012
How are we doing so far (BAO probes)?

Cosmological Distance

Time

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

$z$

Now

BOSS Ly-α

6dFGS

BOSS

SDSS-II

WiggleZ

Dark Energy dynamically important
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 matter distribution
- Redshift information (time)

150 Mpc radius

\(~\text{(CHIME resolution)}\)
Hydrogen Intensity Mapping

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

Radio astronomy

21cm

Redshift: $z = 0.8$
$t = 7$ Gyr

Redshift: $z = 2.5$
$t = 3$ Gyr

NOW ($z = 0$)

Redshift: $z = 0.8$
$t = 14$ Gyr

75cm (400 MHz)

38cm (800 MHz)
What do I build?

z~0.8 HI has been detected in cross-correlation (GBT and WiggleZ/Deep2)

$21\text{cm}$  ~~~~ $38\text{cm}$ (800 MHz)
The Canadian Hydrogen Intensity Mapping Experiment (CHIME)

- 4 cylinders: 20m x 100m
- 1024 dual-polarization feeds
- 400-800MHz
- First light ceremony was Sept 7, 2017!
The Canadian Hydrogen Intensity Mapping Experiment (CHIME)
The Canadian Hydrogen Intensity Mapping Experiment (CHIME)
Front End: Reflector + Feeds

Deng et al, 2014
First light ceremony: Sept 7, 2017!
Front End: Filter Amplifiers

Shipping container
F in FX

Digitizes and channelizes: each channel does a small FFT and produces 1024 frequencies per spatial input.
X in FX

- Reflector
  - Analog Receiver Chain
  - FPGA Digitizer / Channelizer
  - GPU Correlator
    - Disk
    - Real-time Backends

- Water-cooling
2048 x 2048: We make 1024 of these (1 per frequency) every 10s

First correlation matrix!
CHIME - it lives!

Courtesy R. Shaw & S. Siegal
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!
LIMITS ON THE ULTRA-BRIGHT FAST RADIO BURST POPULATION FROM THE CHIME PATHFINDER

CHIME Scientific Collaboration, 1 M. Amiri, 2 K. Bandura, 3, 4 P. Berger, 5, 6 J. R. Bond, 7, 5 J. F. Cliche, 8 L. Connor, 9, 10 M. Deng, 2 N. Denman, 11, 12 M. Dobbs, 8, 7 R. S. Domagalski, 12, 6 M. Fandino, 2 A. J. Gilbert, 8 D. C. Good, 2 M. Halpern, 2, 7 D. Hanna, 8 A. D. Hincks, 2, 13 G. Hinshaw, 2, 7 G. Hsyu, 14 P. Klages, 12, 15 T. L. Landecker, 16 K. Masui, 2 J. Mena-Parrá, 14 L. B. Newburgh, 17 N. Oppermann, 5, 12 U. L. Pen, 5, 7, 18, 12 J. B. Peterson, 19, 12 T. Pinsonneault-Marotte, 2 A. Renard, 12 J. R. Shaw, 2 S. R. Siegel, 8 K. Smith, 18 E. Storer, 8 I. Tretyakov, 12, 6 K. Vanderlinde, 12, 6 and D. V. Wiebe 2

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ABSTRACT

We present results from a new incoherent-beam Fast Radio Burst (FRB) search on the Canadian Hydrogen Intensity Mapping Experiment (CHIME) Pathfinder. Its large instantaneous field of view (FoV) and relative thermal insensitivity allow us to probe the ultra-bright tail of the FRB distribution, and to test a recent claim that this distribution’s slope, $\alpha \equiv -\frac{\partial \log N}{\partial \log S}$ is quite small. A 256-input incoherent beamformer was deployed on the CHIME Pathfinder for this purpose. If the FRB distribution were described by a single power-law with $\alpha = 0.7$, we would expect an FRB detection every few days, making this the fastest survey on sky at present. We collected 1268 hours of data, amounting to one of the largest exposures of any FRB survey, with over $2.4 \times 10^5$ deg$^2$ hrs. Having seen no bursts, we have constrained the rate of extremely bright events to $< 13 \text{sky}^{-1} \text{day}^{-1}$ above $\sim 220 \sqrt{\tau/\text{ms}}$ Jy ms for $\tau$ between 1.3 and 100 ms, at 400–800 MHz. The non-detection also allows us to rule out $\alpha > 0.9$ with 95% confidence, after marginalizing over uncertainties in the GBT rate at 700–900 MHz, though we show that for a cosmological population and a large dynamic range in flux density, $\alpha$ is brightness-dependent. Since FRBs now extend to large enough distances that non-Euclidean effects are significant, there is still expected to be a dearth of faint events and relative excess of bright events. Nevertheless we have constrained the allowed number of ultra-intense FRBs. While this does not...
The Galaxy

Credit: Richard Shaw
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

\{ LBN et al, 2014 \}

Shaw et al 1401.2095
Current state-of-the-art

Cosmological Distance

$\left( \frac{D_V}{r_s} \right)_{\text{fid}}$

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

$\frac{D_V}{r_s}$

$D_V$

$\leftrightarrow r_s$

$D_V$

$\leftrightarrow r_s$

6dFGS

BOSS

WiggleZ

SDSS-II

BOSS Ly-α

Full CHIME

Dark Energy dynamically important

Now

Time
Current state-of-the-art

Cosmological Distance

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

Time

2 Path/5 full year surveys

Now

Dark Energy dynamically important

6dFGS

BOSS

WiggleZ

SDSS-II

BOSS Ly-\( \alpha \)

Full CHIME

CHIME pathfinder
Summary

• Pathfinder has >2 years of ‘data in the can’

• CHIME is nearing the end of its commissioning, have ~1 month of stable data in the can

• Busy analyzing data!
Backup
Why Do We Have to Know the Beams?
Beam map with Holography

Tracking dish
Holographic beam scans from CygA

Analysis by grad student Phil Berger
Holographic beam scans from multiple sources

Berger et al 2016
Building up a beam map

Beam

Source tracks

Simulations courtesy Liam Connor
Building up a beam map

Beam tracks

Simulations by grad student Liam Connor

Actually mapping the NS beam ….

Drones!
Some fun (non Cosmology) numbers

• >110km of coaxial cable
• 135TB/day (we compress via redundant baselines to a mere 0.5TB/day)
• 13Tb/s of data across correlator backplane (6Tb/s total global cellphone traffic in 2014)
• 6.7POps (6x ALMA)
• >100 cows
Current Beam Measurements
allowed region: Planck++
expected allowed region: Planck++CHIME

\[ w(z) = w_0 + w_a \left( \frac{z}{z+1} \right) \]
A Fast Fourier Transform Interferometer

\[ C_{\ell} = \vec{b} \cdot \vec{s} \]

\[ V_1 = V \cos[\omega(t - \tau_g)] \]
\[ V_2 = V \cos(\omega t) \]

\[ V_1 V_2 \rightarrow R = \left(\frac{V^2}{2}\right) \cos(\omega \tau_g) \]

Correlate

‘FFT Telescope’:
Regular correlation: \( \sim N^2 \)
DFFT correlation: \( \sim N \log N \)

(Tegmark and Zalarriaga, 2008)
Can remove them!

Power spectrum errors (400-500MHz)

Shaw et al 1401.2095
(As long as we know our instrument)

Shaw et al 1401.2095

Complex Gain Error

$k_\parallel / h \text{Mpc}^{-1}$

$k_\perp / h \text{Mpc}^{-1}$
(As long as we know our instrument)
• Foregrounds are highly correlated
  • Can change basis into one where that is more apparent with the Karhunun-Loeve transform
  • But, this requires covariance matrices:

10 petabytes of memory

$10^8$
Solution: M-Modes

- Data has periodicity in sky angle (ϕ), 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)
Calibration: Gain and Phase

- 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 each cylinder.
  - It is possible to achieve a relatively flat illumination of the CHIME feeds by pointing the broadcasting antenna to the furthest feed.

Noise Rigidization
It’s a statistical statement

Credit: A. Hincks
It’s a statistical statement

Credit: A. Hincks
Large wavelengths coherently move both galaxies while smaller wavelengths coherently move galaxies at separations defined by the characteristic BAO scale. Eisenstein, Seo and White (2007) point out that the map of galaxies used to reconstruct the position and velocity field can then be used to undo the effect of successively broadening the rings from an acoustic oscillation peak by moving densities to where they would have been had linear theory held at all times. By considering a pair of galaxies separated by the standard ruler length more noisy. Various methods can be followed to reconstruct the velocity field. Since the galaxies are essentially test particles, the effect of successively broadening and shifting the characteristic radius implies an increase in the width of the correlation function bump corresponds to the peak of the correlation function in redshift space. The typical effects make the map of galaxies used to extract the power spectrum in redshift space more noisy.

The typical effects make the map of galaxies used to extract the power spectrum in redshift space more noisy. The typical effects make the map of galaxies used to extract the power spectrum in redshift space more noisy. The typical effects make the map of galaxies used to extract the power spectrum in redshift space more noisy.

\begin{align*}
\xi(r) & \approx 0.5 \left( \frac{r}{D_M} \right) \left( \frac{D_V}{D_M} \right)^2 \\
D_M & = \frac{D_L}{1 + \delta} \\
D_L & = D_{L0} \left( 1 + \frac{z}{1+H_0^{-1}} \right) \\
D_V & = D_{V0} \left( 1 + \frac{z}{1+H_0^{-1}} \right) \\
\delta & = \frac{\Delta M}{D_M}
\end{align*}
What do I build?

Requires highest sensitivity, highest telescope resolution

sources fainter, BAO smaller

redshift: $z = 0.8$
t = 7 Gyr

redshift: $z = 2.5$
t = 3 Gyr

redshift: $z = 0.8$
t = 14 Gyr

NOW
What do I build?

75 cm
50 Mpc $\leftrightarrow$ ~0.5 degrees
Resolution $\sim \lambda/D \rightarrow$ 80m dish!

redshift: $z = 0.8$
$\rightarrow$ t=3 Gyr

redshift: $z = 2.5$
$\rightarrow$ t=7 Gyr

redshift: $z = 2.5$
$\rightarrow$ t=14 Gyr

NOW

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

Beam

North

South

Pulsar tracks

Simulations by grad student Liam Connor