Abstract: CHIME will use the 21cm emission line of neutral hydrogen to map large-scale structure between redshifts of 0.8 and 2.5. By measuring BAO we will place constraints on the dark energy equation of state as it begins to dominate the expansion of the Universe, particularly at redshifts poorly probed by current BAO surveys.

In this talk I will introduce CHIME, a transit radio interferometer designed specifically for this purpose. I will discuss its goals and describe the powerful new analysis techniques we have developed to confront the many challenges of such observations, in particular removal of astrophysical foregrounds which are six orders of magnitude larger than the 21cm signal. A smaller 40m x 37m pathfinder telescope is currently operating at the DRAO in Penticton, BC, and the construction of the full-sized 80m x 100m instrument commenced in early 2015. I will report on current progress, and the lessons already learned.
Probing Dark Energy with the
Canadian Hydrogen Intensity
Mapping Experiment

Richard Shaw
Dark Energy

\[ d_L(z)^2 = \frac{L}{4\pi F} \]

Distance Modulus

- HST Discovered
- Ground Discovered

Inset: Binned Gold data
- High-z gray dust
- Evolution \sim z
- Pure acceleration: \( q(z) = -0.5 \)
- \( w = 1.2, \frac{dw}{dz} = -0.5 \)
- \( w = -0.8, \frac{dw}{dz} = +0.5 \)
- Empty (\( \Omega = 0 \))
- \( \Omega_M = 0.29, \Omega_{\Lambda} = 0.71 \)
Baryon Acoustic Oscillations

- Sounds waves propagating in the early Universe.
- Leave a weak imprint in the matter distribution
- Gives a standard (statistical) ruler
- Exact peak position tells you angular diameter distance and Hubble parameter at the redshift

Sanchez et al. 2012
21cm Intensity Mapping
Cosmological 21cm

- 21cm line is the transition between parallel and anti-parallel spins of neutral Hydrogen
- The ratio between the two occupancies determines the spin temperature $T_S$
  \[ \frac{n_1}{n_0} = \left( \frac{g_1}{g_0} \right) \exp\left( -\frac{T_*}{T_S} \right) \]
- We can observe the contrast relative to the CMB

\[ \Delta T = 23.8 \left( \frac{1 + z}{10} \right)^{1/2} \left[ 1 - \bar{x}(1 + \delta_x) \right] (1 + \delta_b)(1 - \delta_v) \left[ \frac{T_S - T_\gamma}{T_S} \right] \text{ mK} \]
Hydrogen in the Universe

What is the Reionization Era?
A Schematic Outline of the Cosmic History

- The Big Bang
- The Universe filled with ionized gas
- The Universe becomes neutral and opaque
- The Dark Ages start
- The Cosmic Renaissance
- The Dark Ages end
- Reionization starts
- Reionization complete, the Universe becomes transparent again
- Galaxies and Quasars begin to form
- Galaxies evolve
- The Solar System forms
- Today: Astronomers figure it all out!

Dark ages
Reionisation
HI in galaxies
Galaxy Redshift Survey

- Detect all galaxies with high significance.
- Take spectra to determine redshift
Intensity Mapping

- Observe galaxies with a line transition
- Automatically gives redshift

Don’t need to resolve individual galaxies

Chang et al, 2008; Wyithe and Loeb 2008
21cm Intensity Mapping

- In 21cm the frequency gives the redshift.
- Observe the diffuse emission from many unresolved galaxies
- Changes the game in telescope design:
  - Previously: large field of view, large collecting area, large angular resolution (SKA?)
  - Now: large field of view, large collecting area, modest angular resolution (compact arrays, single dishes).

Foreground Challenges

Cosmological 21cm Signal ~ 1mK
Foregound Challenges

Cosmological 21cm Signal ~ 1mK
Foreground Challenges

Galaxy: up to 700K
Mode mixing

High frequency

Low frequency

Sum along angular direction

Instrumental beam

angular direction

frequency

intensity
Canadian Hydrogen Intensity Mapping Experiment
CHIME Overview

- Located at DRAO in BC
- Transit radio interferometer
  - Observe between 400-800 MHz
  - 0.4 MHz spectral resolution
  - 1024 dual pol antennas ($T_{\text{recv}} = 50K$)
- 120 x 2 degree FoV
Survey Volume

- **WiggleZ**: $1.2 \, (h^{-1} \, Gpc)^3$
- **BOSS**
  - LRG: $5.3 \, (h^{-1} \, Gpc)^3$
  - Lyα: $37 \, (h^{-1} \, Gpc)^3$
- **CHIME**: $203 \, (h^{-1} \, Gpc)^3$
- **DESI ELG**: $50 \, (h^{-1} \, Gpc)^3$

Scaled such that:

area of patch = volume of survey
BAO Forecasts

![Graph showing BAO Forecasts](image)

- **Powerspectrum constraints**
- **Distance constraints**
BAO Forecasts

![Graph showing BAO Forecasts with different redshifts and velocities](image)

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

![Graph showing ratios of velocities and redshifts](image)

- Full CHIME
- BOSS Ly-α
- CHIME pathfinder
CHIME Status

- Construction completed!
CHIME Pathfinder
CHIME Pathfinder

- 2x20m cylinder, 40m long
- First light was late 2013
- Pathfinder analysis ongoing
Data Analysis with the m-mode formalism

Data Analysis

- Analysis is challenging:
  - Wide field at given instant \((\sim 120 \times 2 \ degrees)\)
  - Effectively an all sky survey \((3\pi \ sr)\)
  - Data volume \((\sim 1 \ TB/day \ for \ pathfinder)\)
  - Polarisation leakage
  - Foreground removal \((\sim 10^6 \ times \ brighter)\)
Interferometers

- Visibility is instantaneous correlation of 2 antennas

\[ V_{ij} = \langle F_i F_j^* \rangle \]

- Written explicitly:

\[ V_{ij}(t) = \frac{1}{\Omega_{ij}} \int d^2 \hat{n} A_i(\hat{n}; t) A_j^*(\hat{n}; t) e^{2\pi i \hat{n} \cdot \mathbf{u}_{ij}(t)} T(\hat{n}) \]

- Traditional analysis approximates this to a 2D Fourier transform and proceeds from there.

\[ \Delta \phi = 2\pi \hat{n} \cdot \mathbf{d}_{ij}/\lambda \]
Foreground Cleaning

Unpolarised Foreground  Polarised Foreground (Q)  21cm Signal

Foregrounds 10^6 times larger than signal
Foreground Cleaning

Foreground residuals significantly smaller than signal
Foreground Cleaning

Unpolarised Foreground  |  Polarised Foreground (Q)  |  21cm Signal

Foregrounds $10^6$ times larger than signal
2D Power spectrum Estimation

No FG

Full FG

Fractional powerspectrum errors (blue is better)

Subtraction works well into foreground wedge
Summary

- BAOs are an alternative probe of dark energy
- 21cm Intensity Mapping is a promising technique for mapping the Universe and measuring BAOs - foregrounds are challenging
- CHIME Pathfinder is operating, full instrument construction finished summer 2015
- Analysis is fun! Polarised radio sky simulation and 21cm data analysis code all available at:
  
  http://github.com/radiocosmology/