The CHIME Dark-Energy Project

CAP Congress 2015

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Outline

- motivation - measurement of expansion history of the Universe to learn about Dark Energy

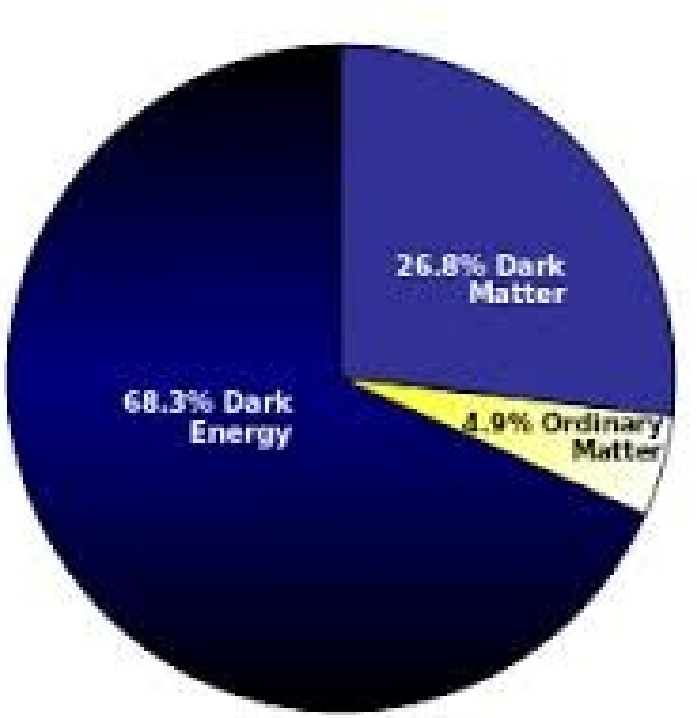
- baryon acoustic oscillations - a standard ruler

- hydrogen intensity mapping - a quick way to map large-scale structure

- experimental design - a digital radio telescope

- progress to date - pathfinder up and running; main instrument under construction

- but wait, there's more! - pulsars and fast radio bursts



CHIME Collaborators

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Motivation

- the Universe is expanding and the rate is increasing

- could be due to cosmological constant or dark energy

- need to figure out which

The rate of expansion is a function of the mass-energy densities of the basic constituents of the universe (dark matter, baryons, photons, etc.)

$$H \equiv \frac{\dot{a}}{a} = \sqrt{\sum_x \frac{8\pi G}{3}\rho_x(a)}$$

Each consituent has an equation of state $p_x = w_x \rho_x$.

$$\rho_x(a) \propto \exp\left[-3\int_1^{1/a-1}[1+w_x(a')]\,\frac{da'}{a'}\right]$$

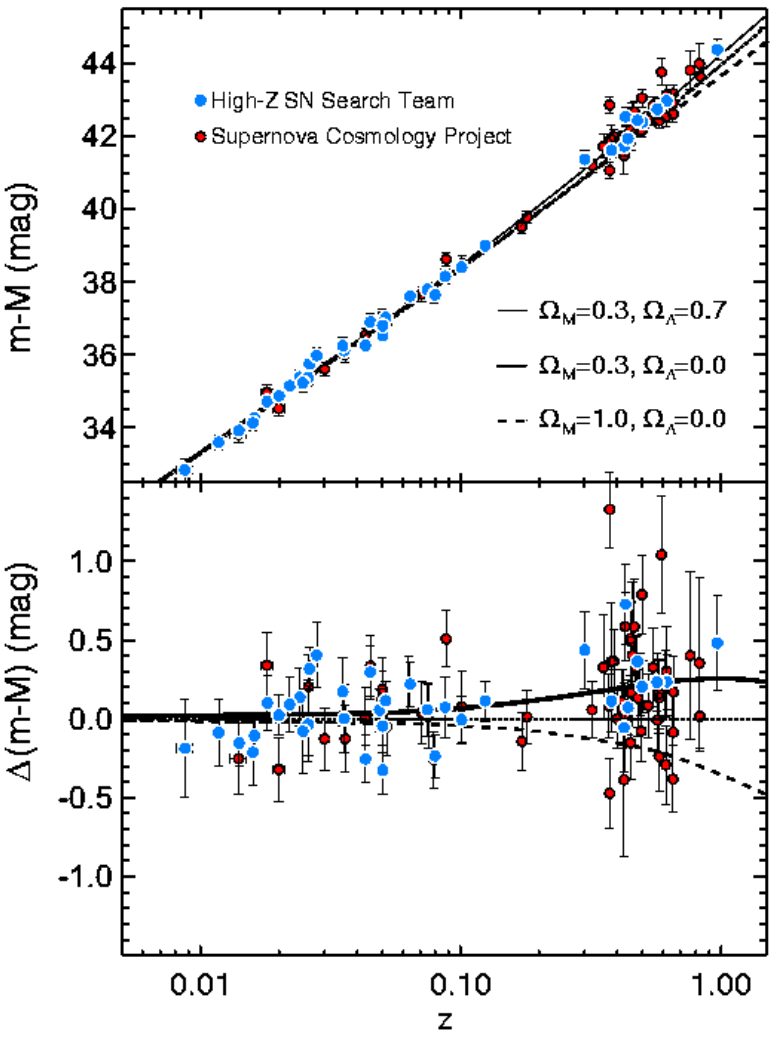
For acceleration, we need $w(a) < -1/3$.

Einstein's gravitational equation can have a constant of integration:

$$G_{ab} + g_{ab}\Lambda = 8\pi T_{ab}$$

A cosmological constant Λ has constant energy density:

$$w_\Lambda(a) = -1 \longrightarrow p_\Lambda = -\rho_\Lambda$$

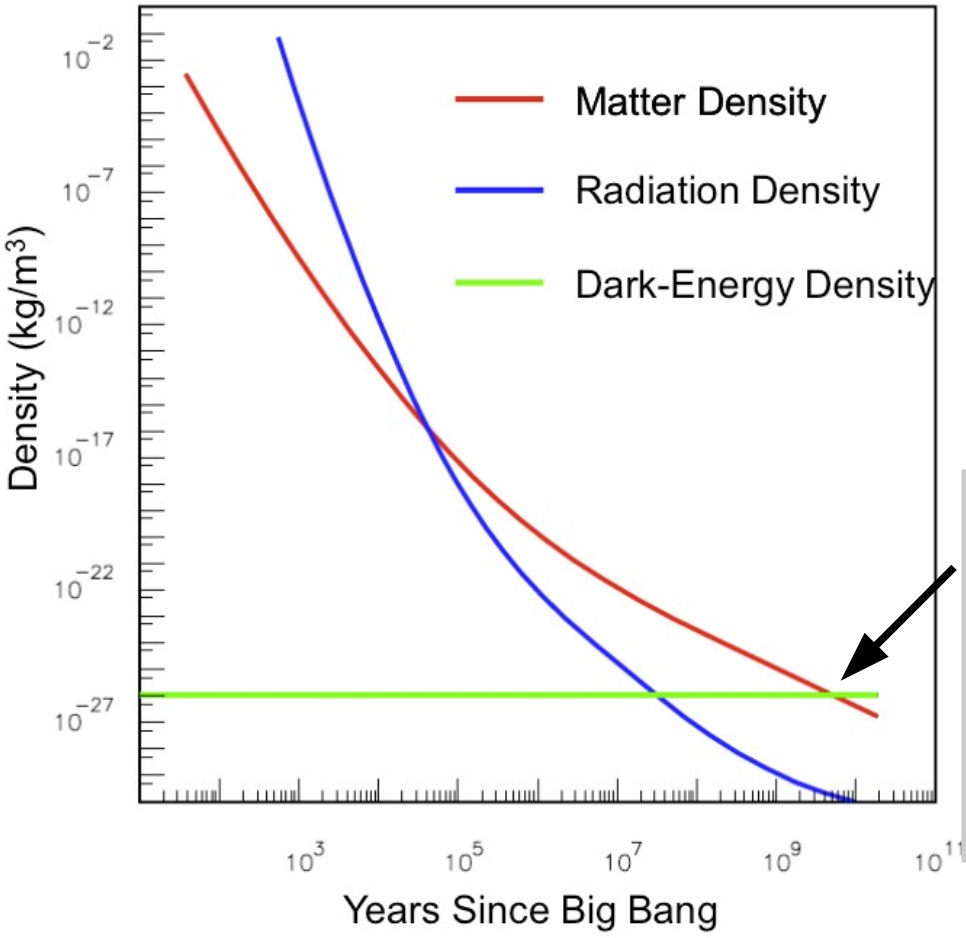


note the z scale !

Measure H as a function of time over a cosmologically interesting range

$$H(z) = \sqrt{\sum_x \frac{8\pi G}{3}\rho_x(z)} \propto \sqrt{\sum_x \frac{8\pi G}{3} \exp\left[3\int_0^z [1+w_x(z')]\frac{dz'}{1+z'}\right]}$$

We do not measure H directly. Things we *can* measure are redshifts, apparent magnitudes and angular sizes.



Measure here for best results

- slowing down from gravity pulling back

changes to

- speeding up due to dark energy pushing apart

What to measure?

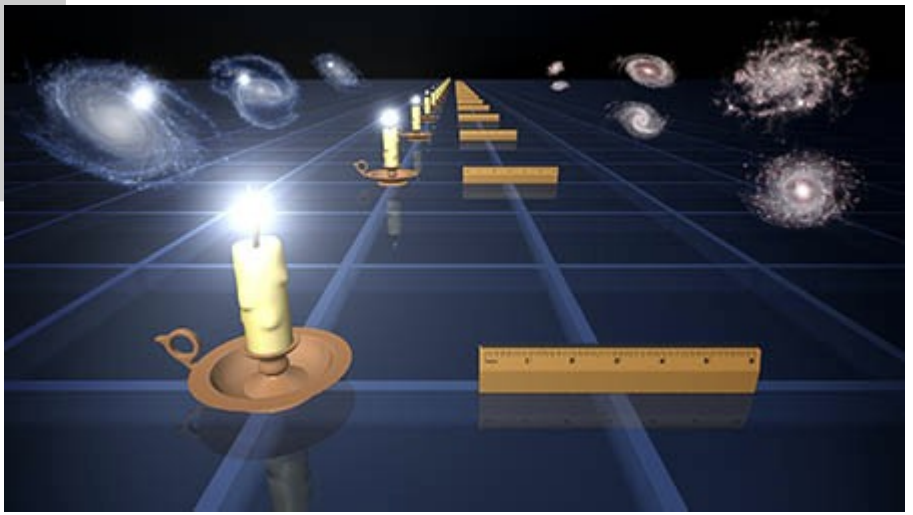
the baryon acoustic oscillation feature
- it's a standard *ruler*

- its physical size, *l* , is calculable, measurable, and expands at the same rate as the Universe

$$D_A = \frac{l}{\theta} \propto \frac{1}{(1+z)} \int_0^z \frac{dz'}{H(z')}$$

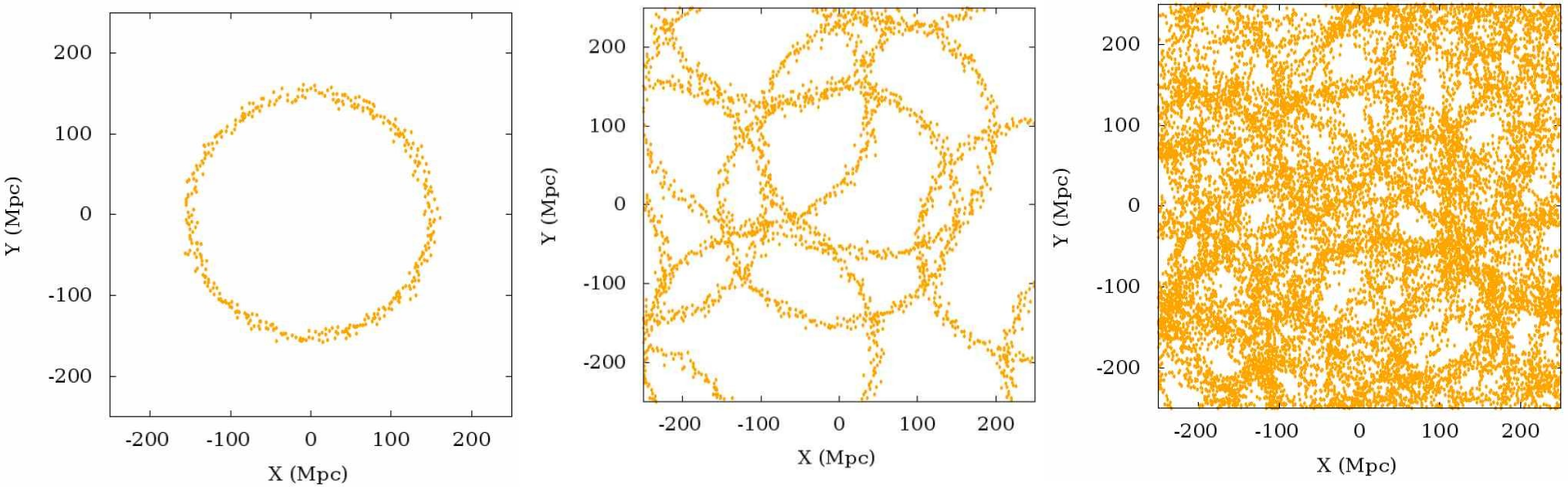
- measure z and θ

- compute the rest



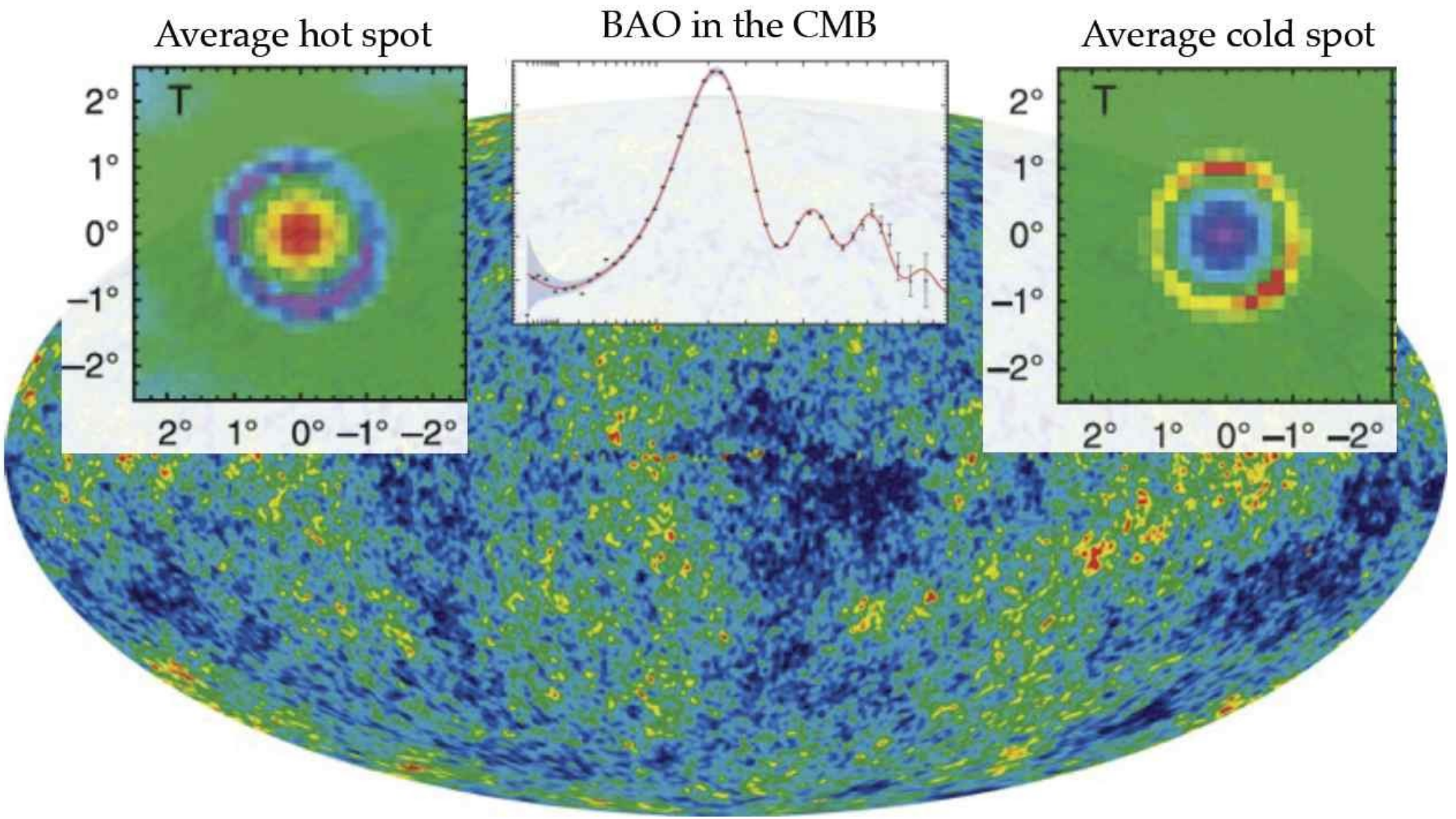
Baryon Acoustic Oscillations

- immediately after the Big Bang the Universe was filled with a hot, dense plasma
- 'cosmic sound' waves propagated in this medium
- when the Universe had expanded and cooled enough to allow neutral hydrogen to form
    - cosmic microwave background was released
    - BAO peaks 'froze' at a characteristic scale
- the slight overdensities at the wave-fronts give rise to large-scale-structure



(Komatsu et al., ApJ, 2011)

(Hinshaw et al., ApJ, 2009)



BAO have been observed in the CMB, and set the acoustic scale: $l_A = 302.69 \pm 0.69$ @ z_*=1091.

$$l_A = (1 + z_*)\frac{\pi D_A(z_*)}{r_s(z_*)},$$

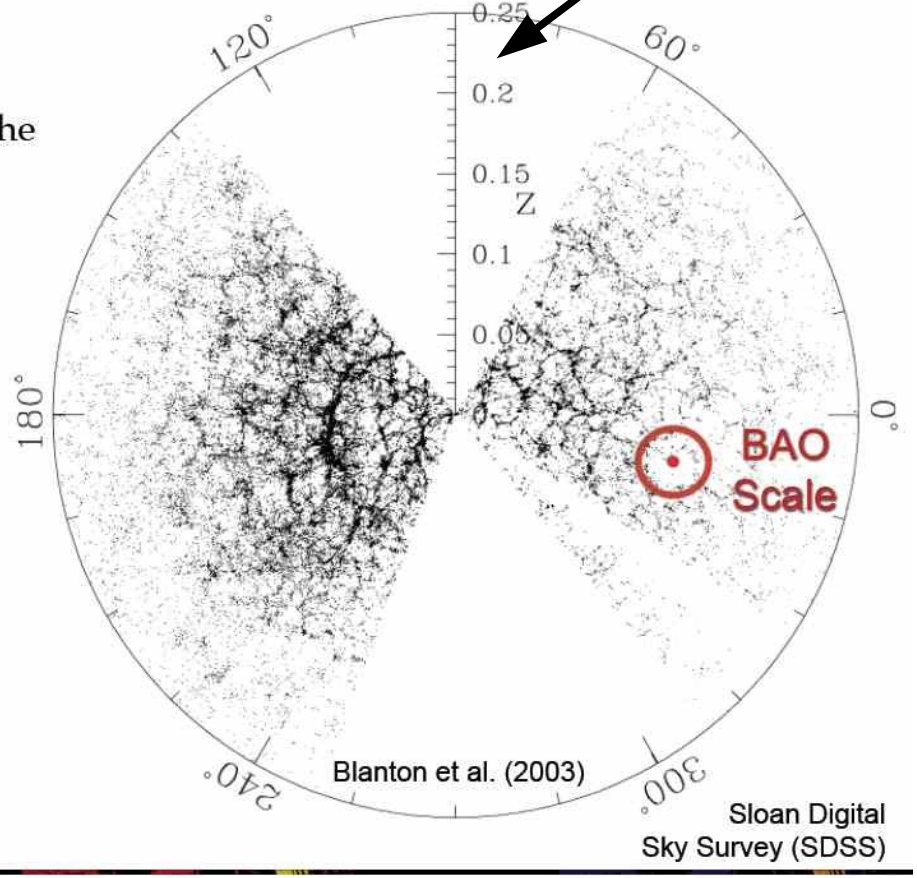
Baryon Acoustic Oscillations

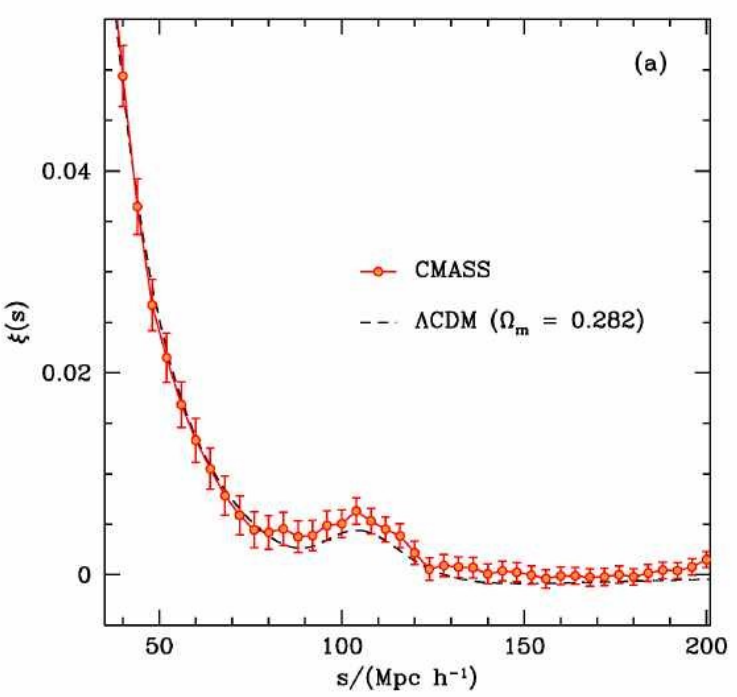
- have already been seen in the CMB

- also in large-scale structure using galaxy surveys

keep looking at the z scale

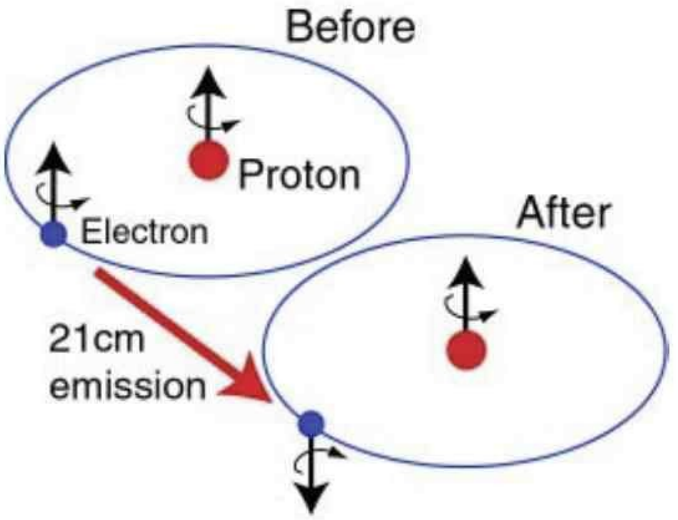
The BAO scale schematically superposed on the SDSS galaxy distribution.





To use the BAO feature for Dark Energy tests we want to go to larger z

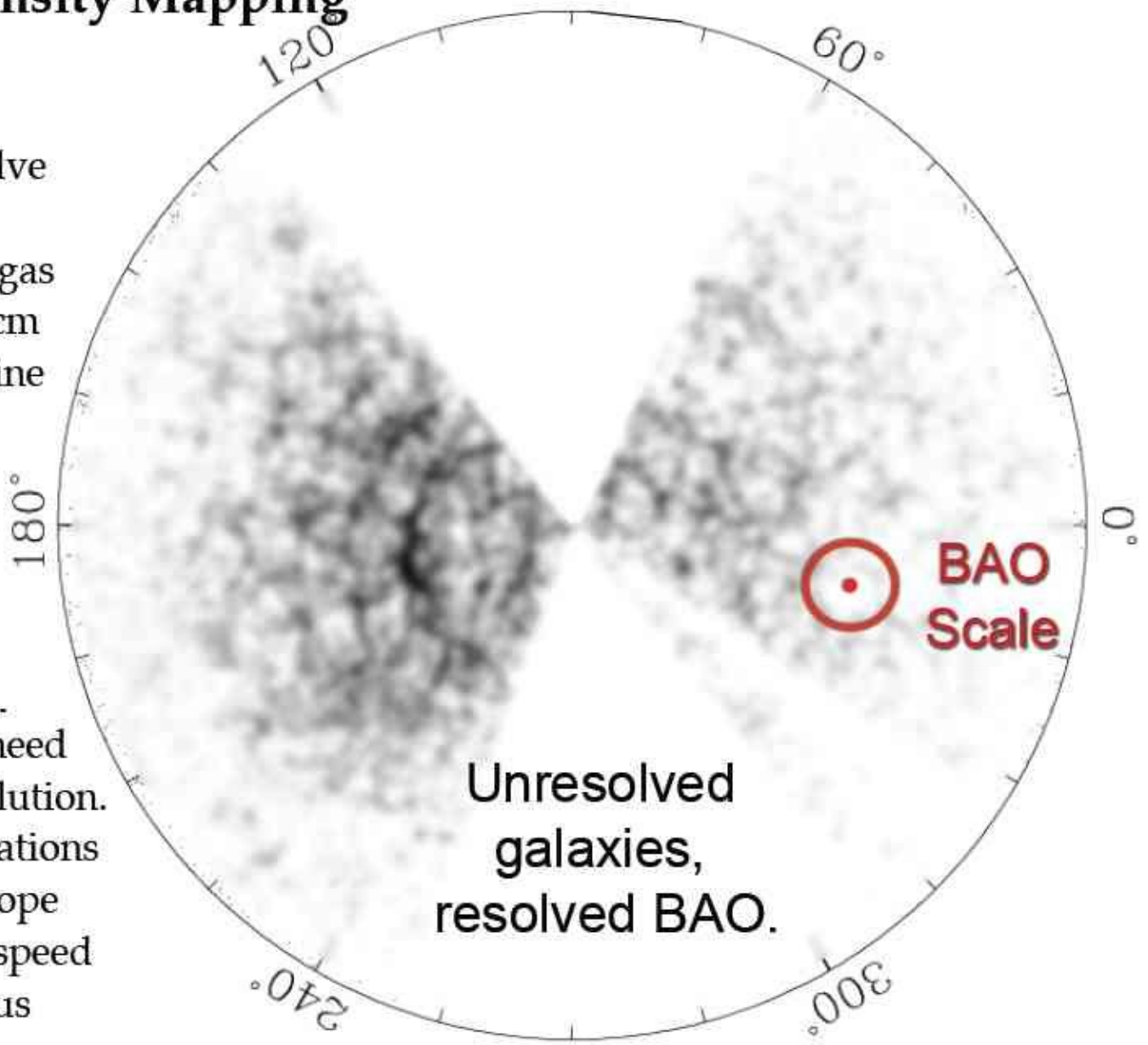
- SDSS-type measurements get more difficult
  - galaxies are fainter and redder
  - measurements take longer
- a new approach is needed : Hydrogen Intensity Mapping
  - neutral hydrogen is the most abundant commodity in the Universe
  - it traces the large-scale structure (gravitationally attracted)
  - it emits spin-flip radiation at 21 cm in its rest frame
  - measure this line at a given frequency and automatically get the red-shift - no need for spectroscopy



Hydrogen Intensity Mapping

To measure BAO in LSS, no need to resolve individual galaxies. Map intensity of HI gas using redshifted 21 cm emission along the line of sight.

For 15 Mpc spatial resolution at z~1-2, need ~15-25′ angular resolution. This requires observations with a ~100 m telescope and a **fast** mapping speed in a nearly continuous 400-800 MHz band.



CHIME - the Canadian Hydrogen Intensity Mapping Experiment

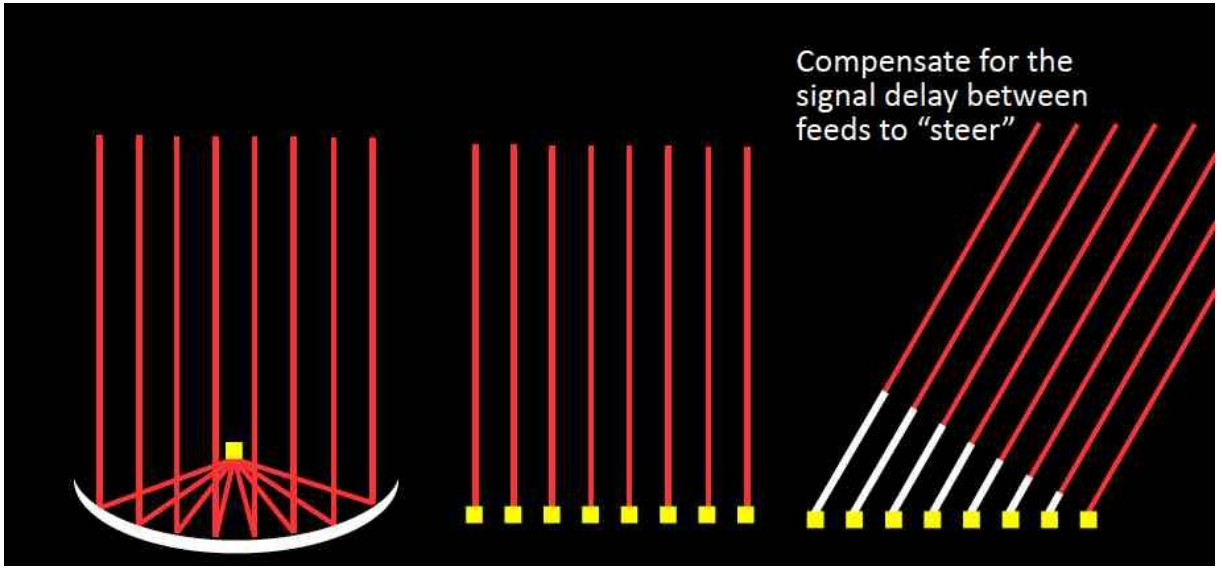
- a transit telescope - no moving parts - scans the sky every day

- four 100 m by 20 m parabolic cylinders focus radio waves onto lines of receivers

- 256 receivers (dual-polarization) 'feeds' per cylinder

- frequency range: 400 MHz - 800 MHz (z = 0.8 - 2.5)

- multiple beams are formed electronically (adding feed-specific delays)

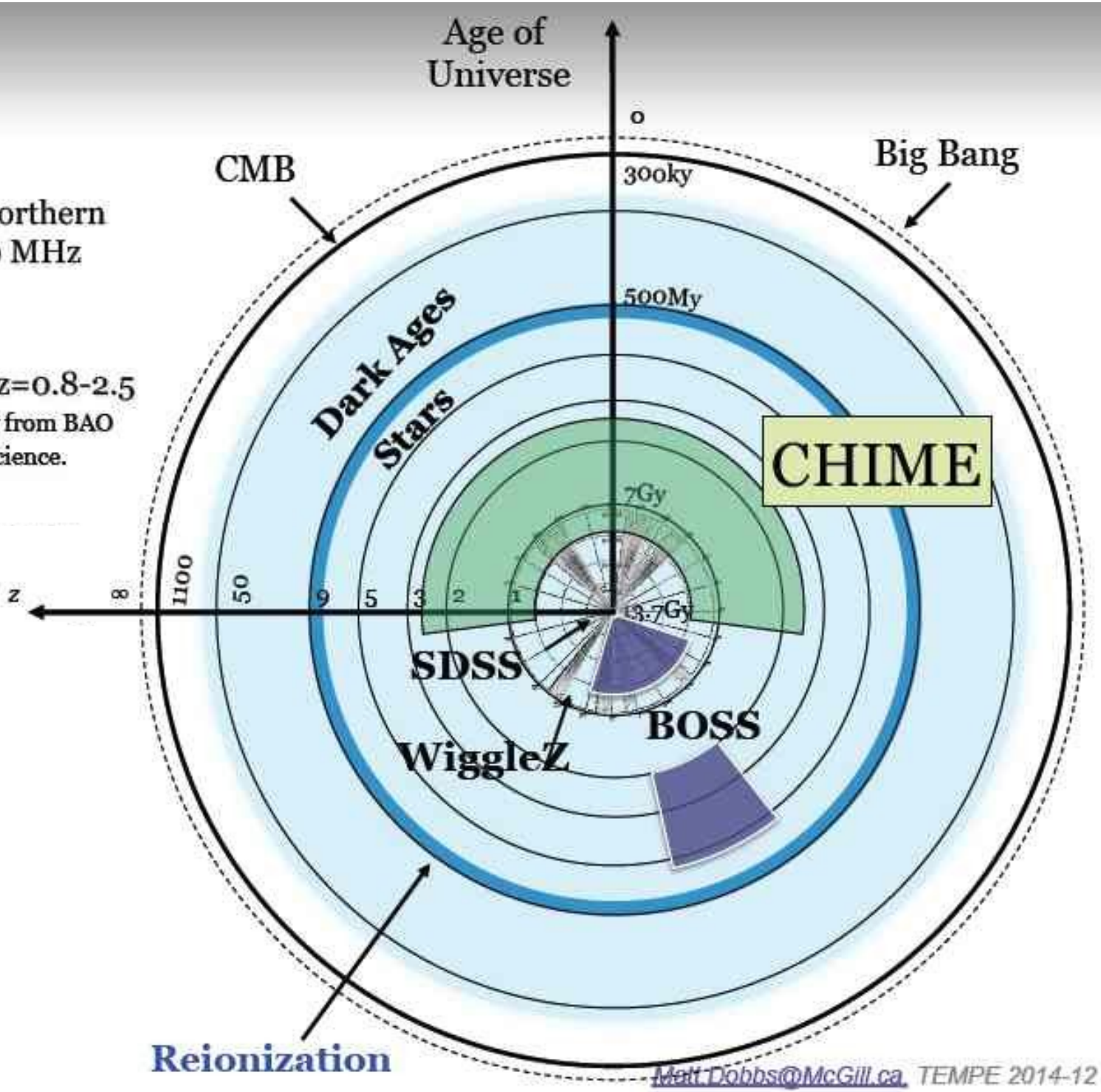


CHIME - scans the northern sky in three dimensions

- north-south using different delays
- east-west every 24 hours as the Earth rotates
- near-far by using the red-shift of the 21-cm line (400-800 MHz ; $0.8 < z < 2.5$)
- will map the largest volume of the Universe so far

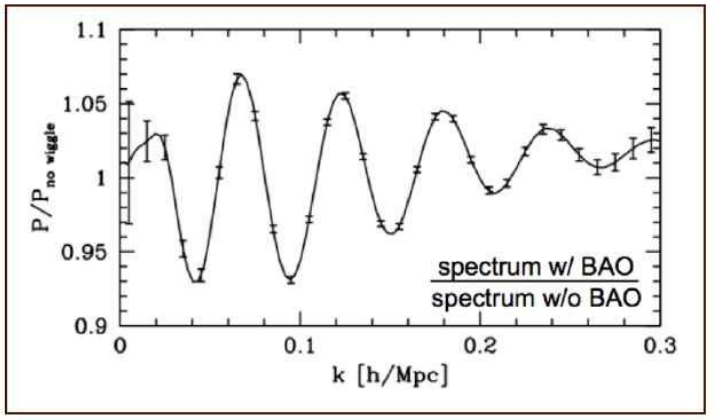
CHIME:

- I,Q,U across the northern sky from 400-800 MHz
- 3D map of matter distribution from z=0.8-2.5
  - → Expansion history from BAO
  - → Rich correlation science.

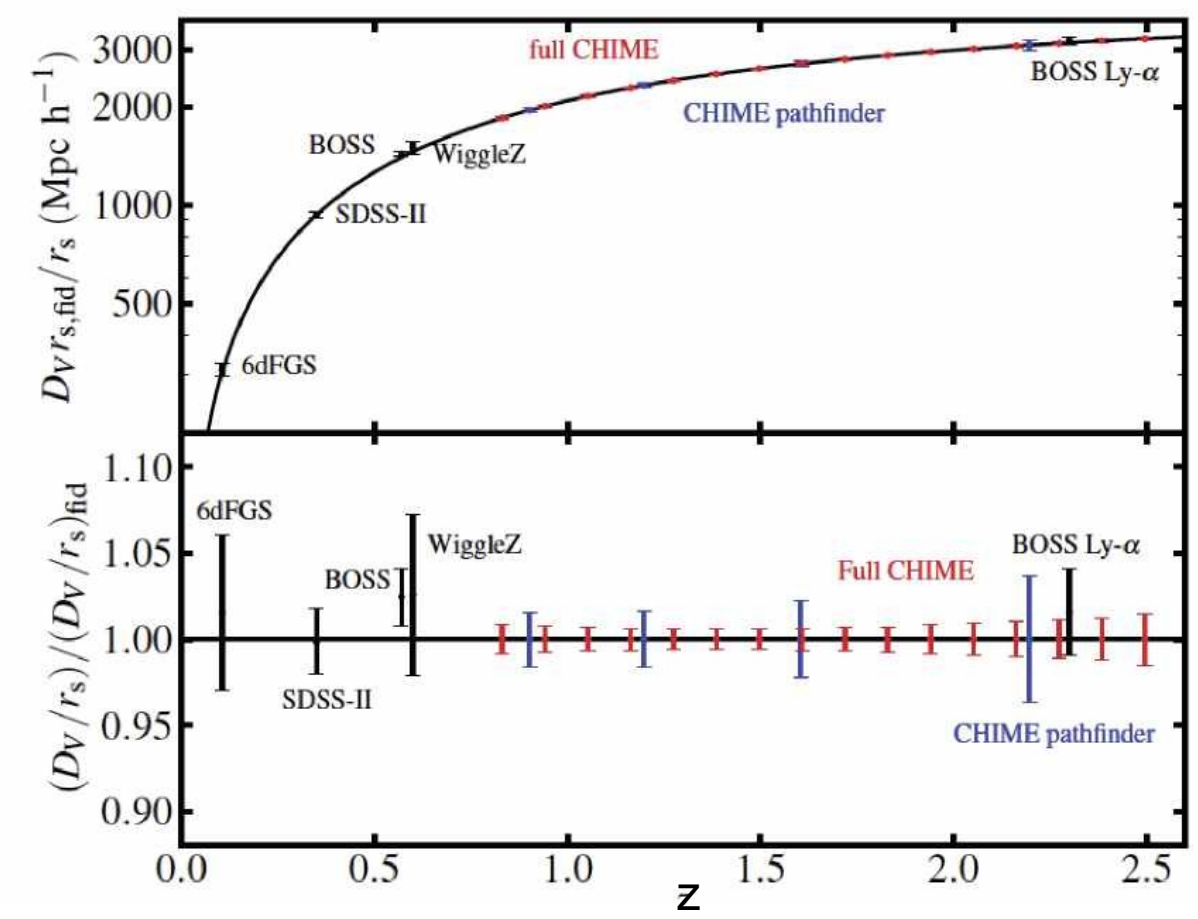


Money Plots:

- what we hope to achieve



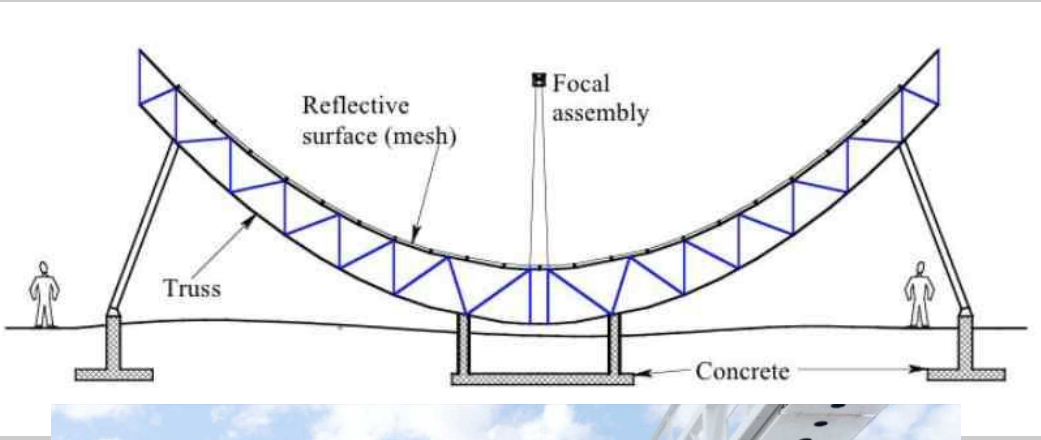
- *Line* – BAO (ΛCDM) in Fourier space, projected onto one effective redshift.
- *Errorbars* – Predicted 2-year sensitivity of CHIME.

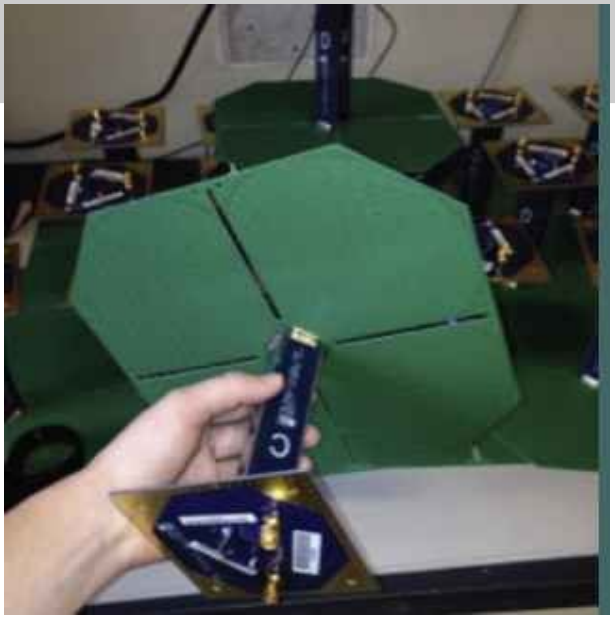


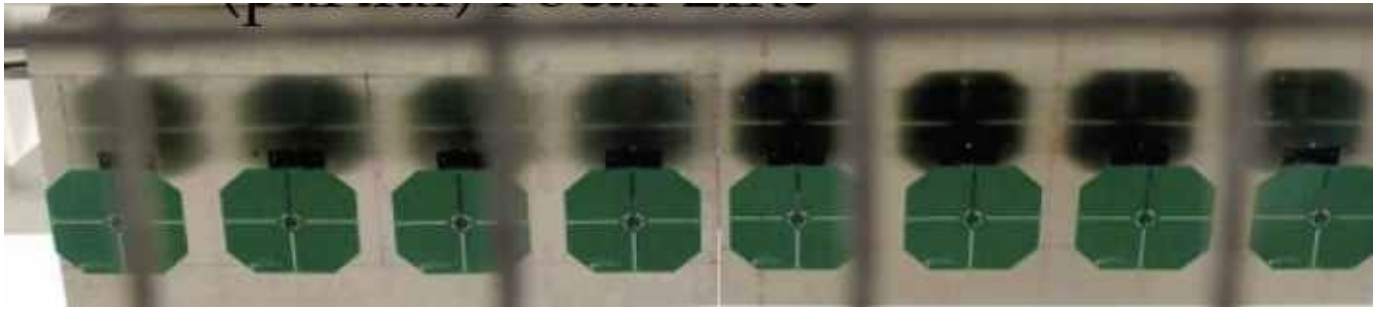
CHIME technology

- steel frame with mesh surface

- clover-leaf feeds along focal line

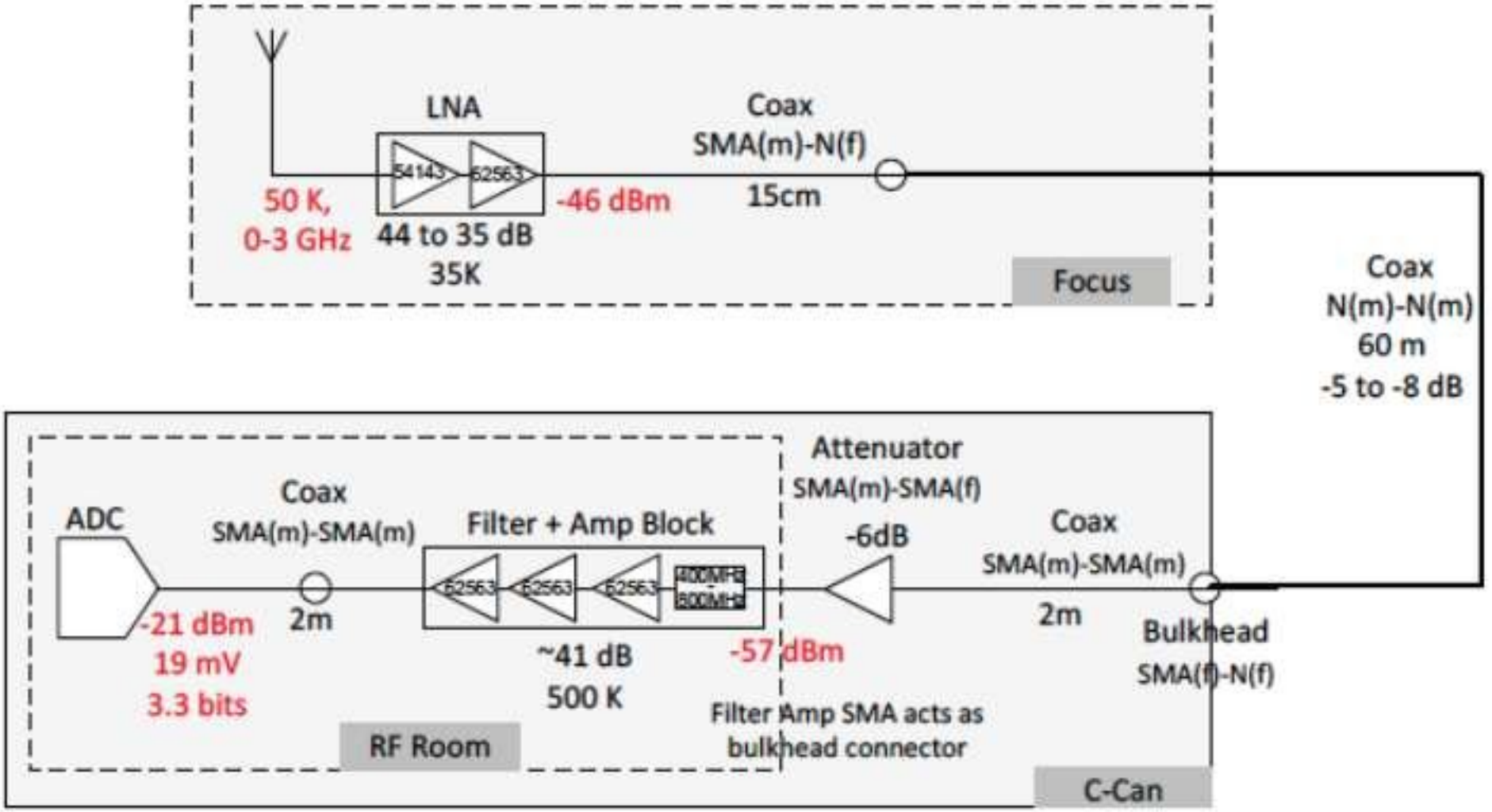






CHIME technology

- analog electronics

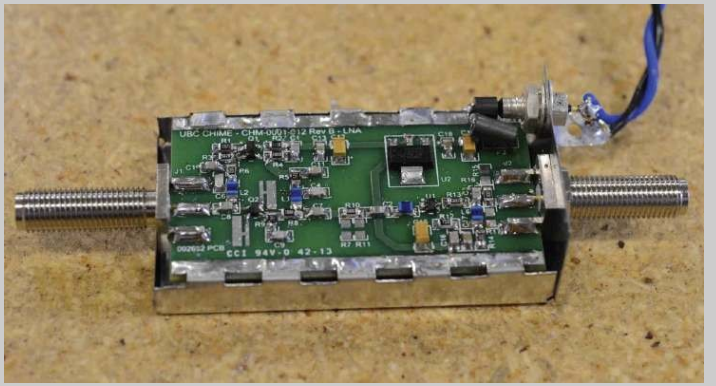


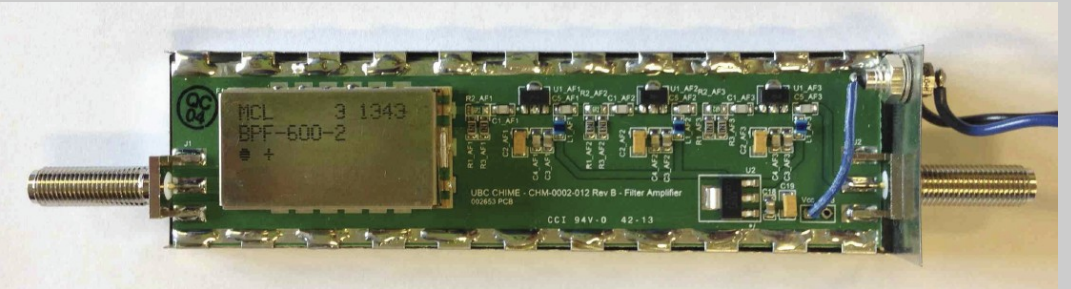
CHIME technology

- custom electronics - developed by collaboration members

- low-noise amplifier

  - on the feed at the focal line
  - based on cell-phone transistors (< 1$)



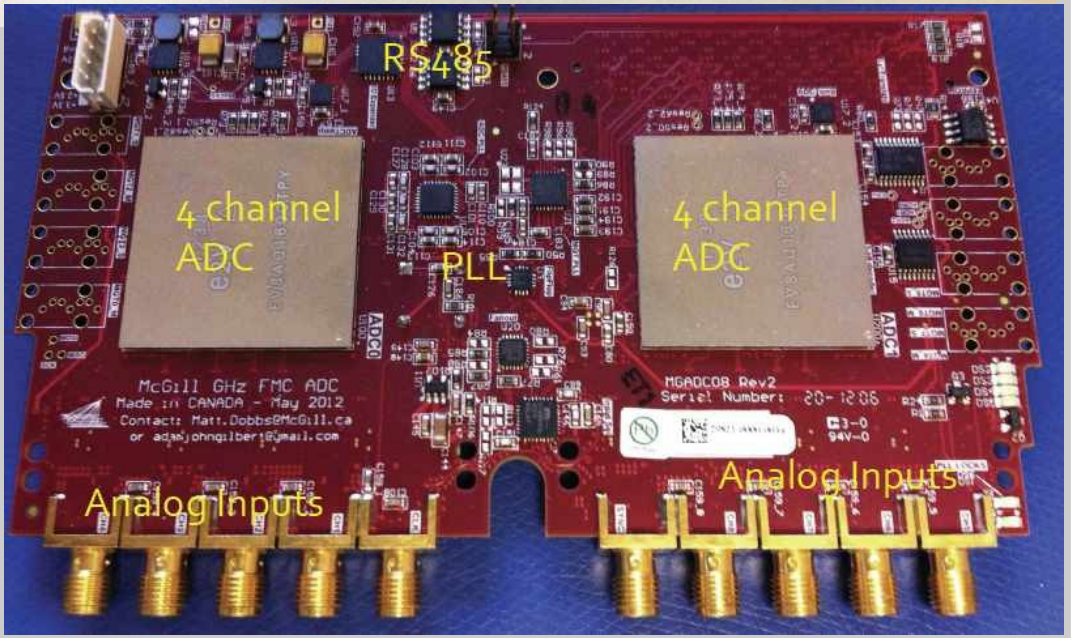


- filter-amplifier

  - at the electronics hut
  - selects the 400-800 MHz range

- digitiser

  - 800 MS/s FADC
  - dynamic range allocation



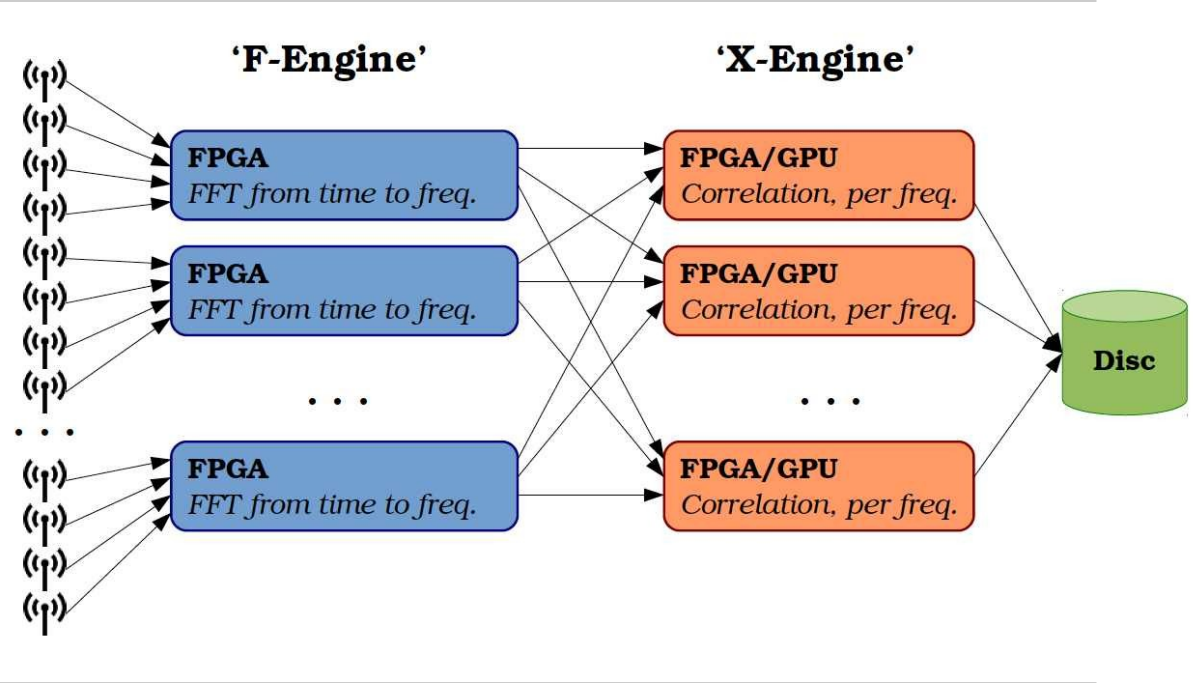
CHIME signal processing - FX correlator

F-engine

- based on FPGAs

- computes Fourier transform

- decomposes signal into 1024 frequencies between 400 and 800 MHz



X-engine

- combines signals pairwise to compute correlation products

- approximately 2M products to be computed - on the fly!

- uses GPUs (32)

- cheap, fast hardware (big power bill)

CHIME progress

- located at Dominion Radio Astrophysical Observatory (DRAO) in Penticton, BC (a radio-quiet area shielded by terrain and protected by legislation)

- preliminary studies 2011-13 with two-dish system

- pathfinder funded by NSERC (RTI) and universities

- CHIME fully funded by CFI (~$11M)

- pathfinder built 2013-14 at DRAO, now being understood

Pathfinder

- two cylinders, 20 m by 35 m

CHIME progress

- full CHIME now under construction

- photos from June 8-9

Extra science - Pulsars and Radio Transients

CHIME will be one of the largest radio telescopes in existence
and will scan the northern sky every day

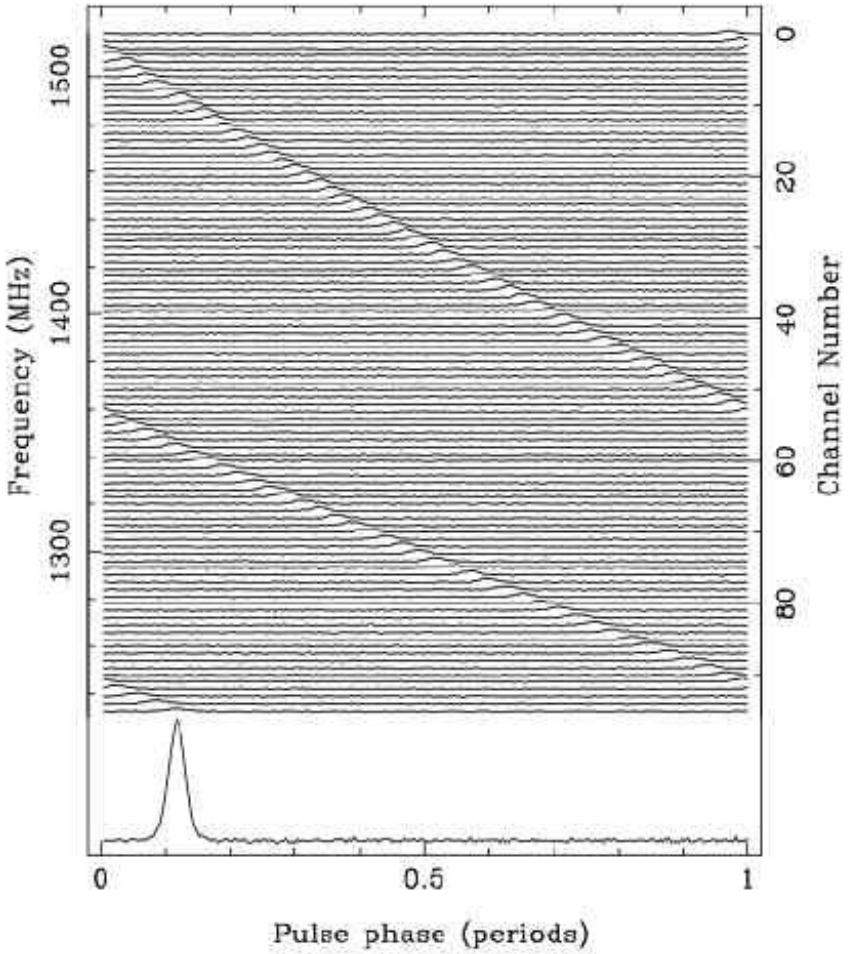
- excellent for monitoring known pulsars and looking for new ones

- siphon off the same signals as used for cosmology and send to a dedicated “pulsar back-end” - limited number of beams

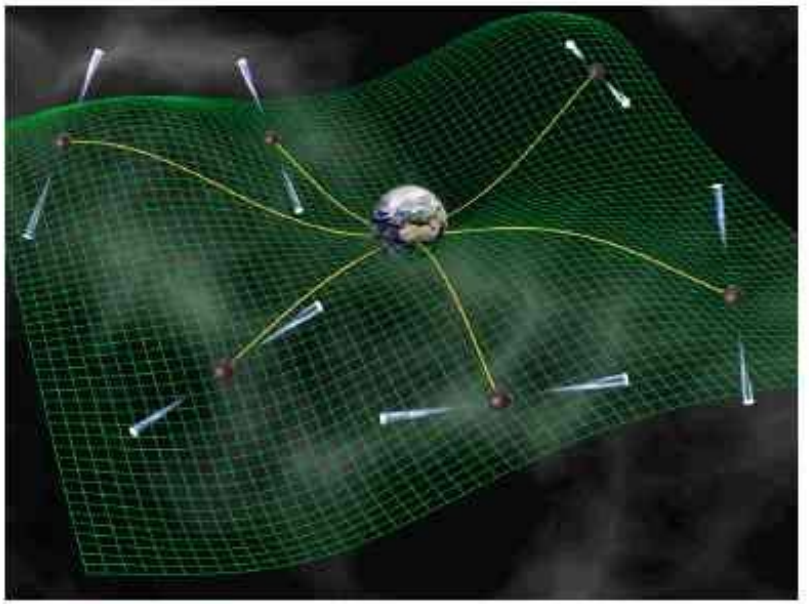
- one was funded for the pathfinder (NSERC RTI)

- one recently funded for full-CHIME (CFI ~ $2.5 M)

Pulsar Monitoring & Detection



- Daily coverage of ~1/2 sky
- Monitor known pulsars for residuals or dispersions

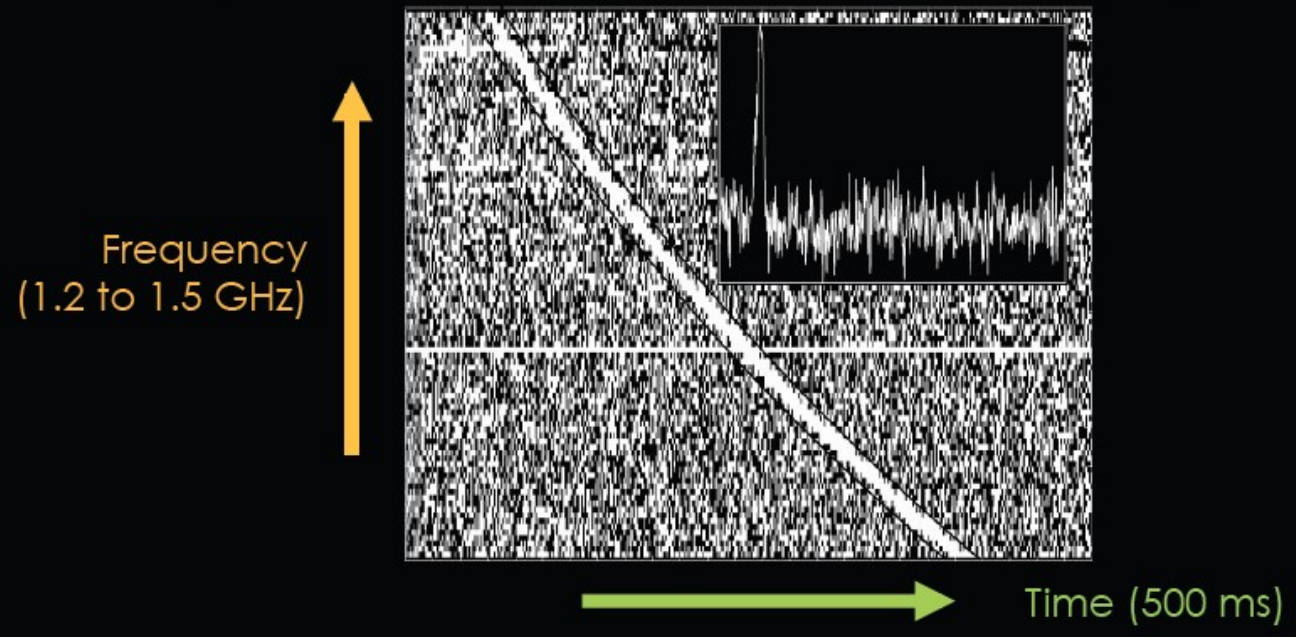


millisecond pulsars are Nature's most precise celestial clocks

measuring times-of-arrival from a suite of pulsars can be used to search for evidence of low-frequency gravity waves

The ‘Lorimer Burst’

- Such a signal was discovered as a single bright pulse by Lorimer (2007) in Parkes Multibeam Pulsar Survey data
- Dispersion far too high to be explained by Galactic interstellar medium alone
- Interpreted as extragalactic—even cosmological



Fast Radio Bursts

- radio astronomy's version of the gamma-ray-burst mystery
- small numbers of one-off events
- need for a large instrument to get a real understanding
- fast de-dispersion and large collecting area are key
- some models predict CHIME will see thousands per day

Challenges

- the tyranny of large N

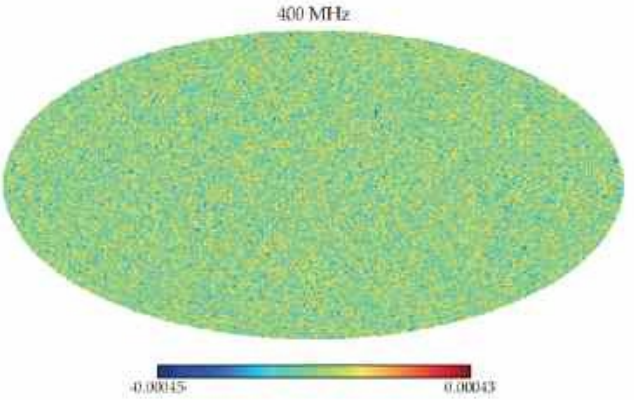
    - FT calculations scale as N^2

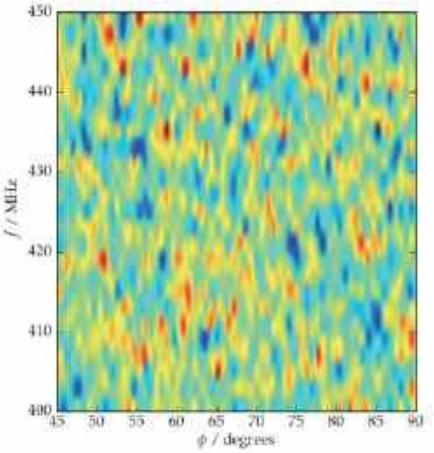
    - FFT calculations scale as Nlog(N) but needs an excellent understanding of the instrument and its calibration in real time

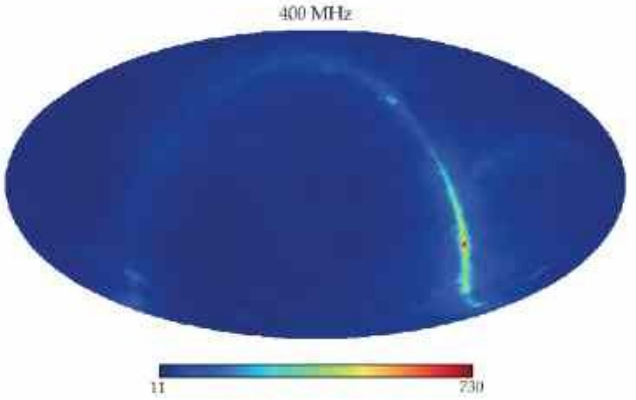
- galactic foregrounds

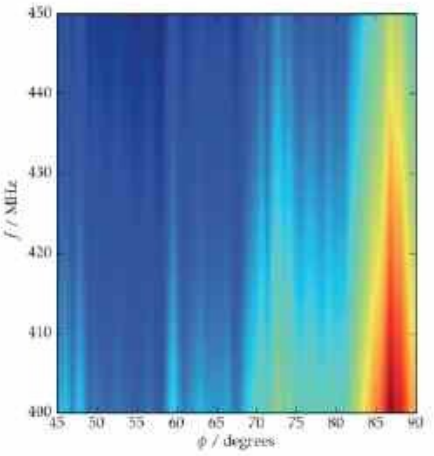
    - cosmology signal: ~ 1mK

    - galactic signal: up to 700 K









Summary

- Dark Energy is a key question in physics, especially cosmology

- BAO studies are the best way to survey the Universe at distances where Dark Energy became an important player in the history of the Universe

- hydrogen intensity mapping is a fast and economically advantageous way of measuring the BAO but is technically challenging

- CHIME is on course to making a huge contribution to this exciting endeavor