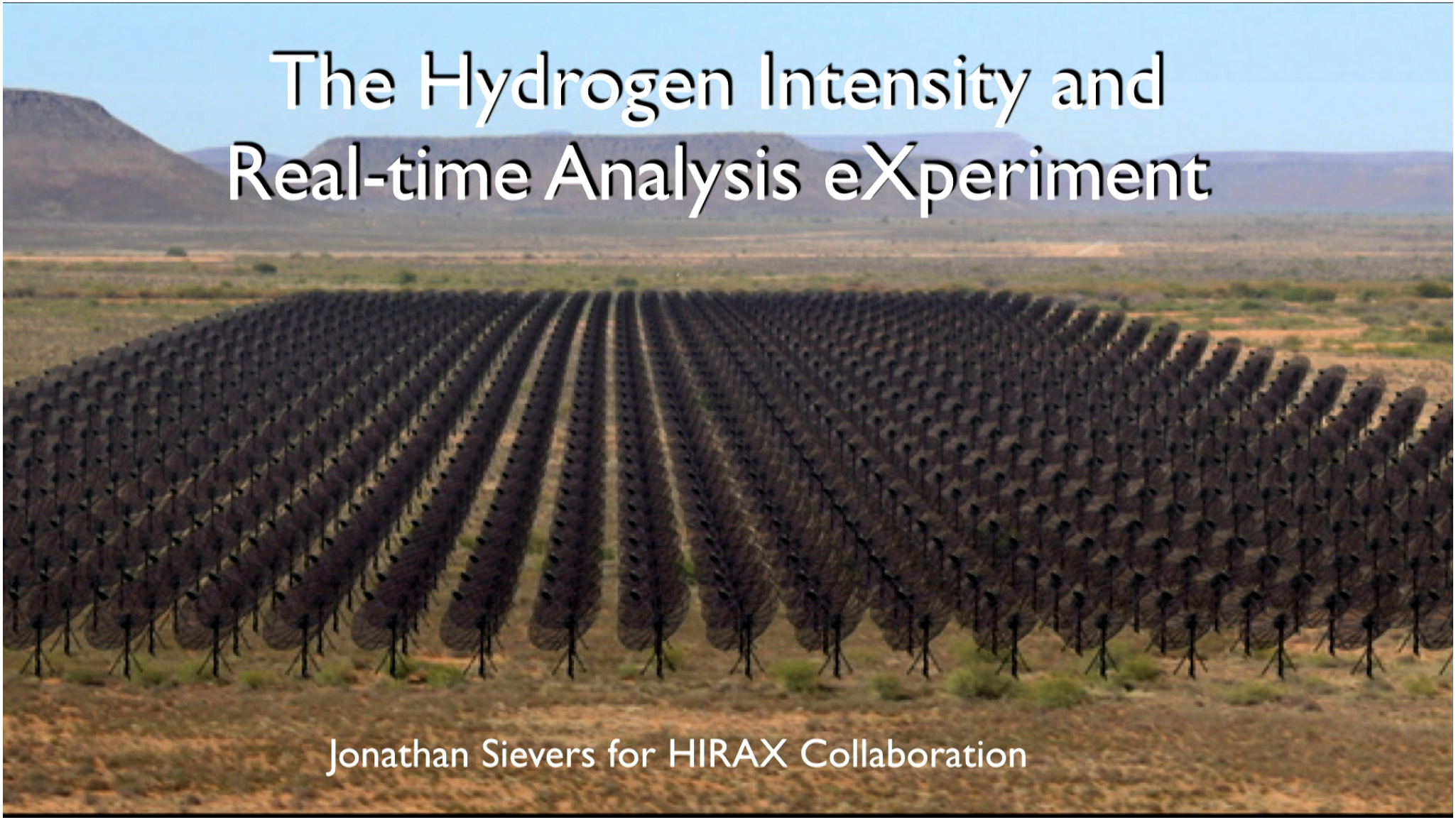
Title: HIRAX: The Hydrogen Intensity and Real-time Analysis eXperiment

Date: Sep 11, 2017 02:00 PM

URL: http://pirsa.org/17090058

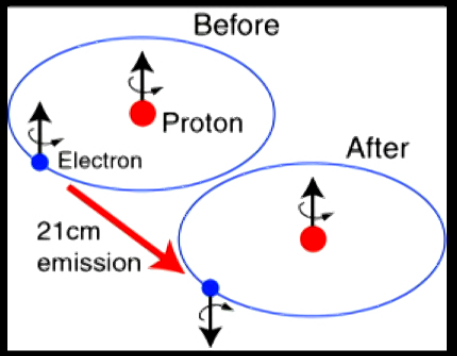
Abstract: The 21cm transition of atomic hydrogen is rapidly becoming one of our most powerful tools for probing the evolution of the universe. The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) is a planned 1,024-element array to be built in South Africa that will study the (possible) evolution of dark energy from z=0.8 to 2.5. Its design also makes it an excellent pulsar and fast radio burst (FRB) search machine. While the FRB rates in the HIRAX band are uncertain, we expect it will discover dozen(s) per day. HIRAX will use inexpensive 6m satellite television-class dishes. The same dishes can be used to build relatively inexpensive outrigger stations in southern Africa to localize a large fraction of the FRBs discovered by HIRAX to ~0.1 arcseconds, potentially transforming them into probes of the universe.


The Hydrogen Intensity and
Real-time Analysis eXperiment
Jonathan Sievers for HIRAX Collaboration

25 institutions across the planet (8 in RSA)

http://www.acru.ukzn.ac.za/~hirax/

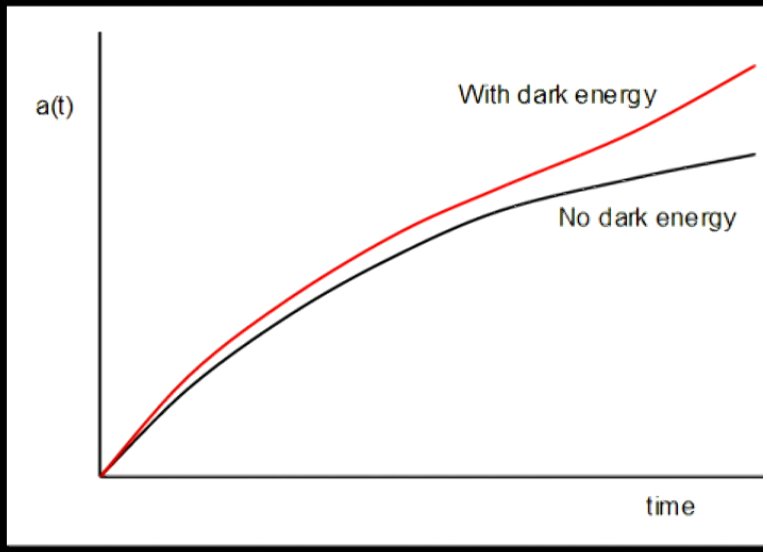
21 CM Transition

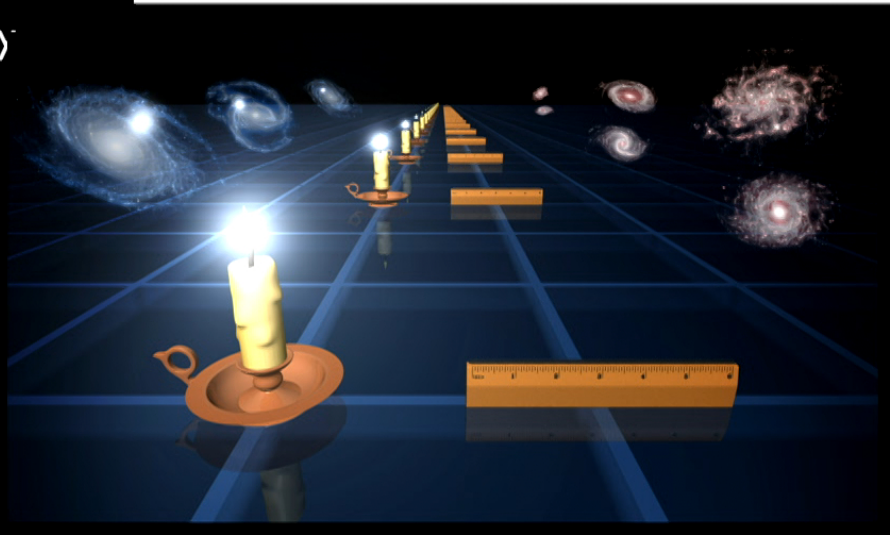


- Neutral (atomic) hydrogen (HI to astronomers) has a spin-flip transition. Electron spin aligned with proton, then flips to opposite spin.
- Energy very small - rest wavelength is 21 cm (1.4 GHz)
- Transition is forbidden, lifetime of excited state is about 10 million years.
- Long lifetime means kinetic temperature T_k (atomic motions) can decouple from spin temperature T_s, set by fraction of HI.
- No 21 cm from molecular hydrogen H_2, or ionized hydrogen.

Standard Rulers

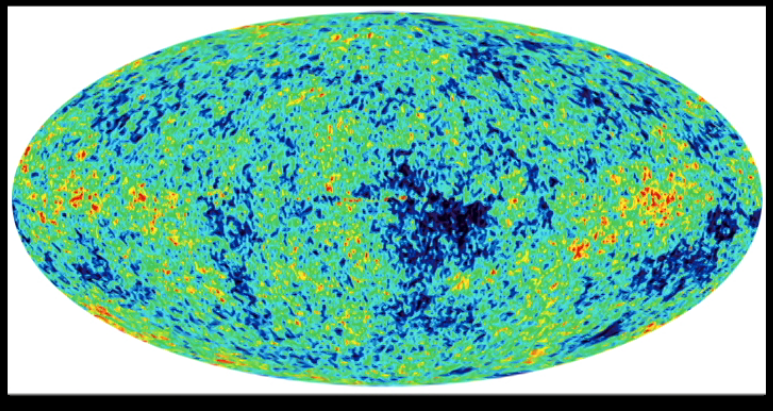
- We can use hydrogen to learn about dark energy.
- One way to measure dark energy is with standard rulers.
- Apparent size of objects of known physical size depends on dark energy.
- By tracing out size of rulers, we can describe dark energy
- If only we had a population of things whose size we knew…





Early On…

- Before CMB, fluctuations are sound waves.
- Gravity drives collapse, photon pressure provides restoring force.
- Photons coupled to matter by free electrons. They disappear at recombination.
- Wave properties get locked in when electrons go away.



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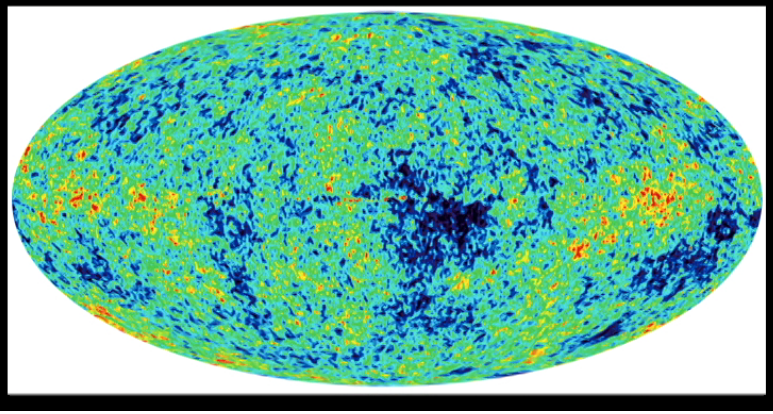
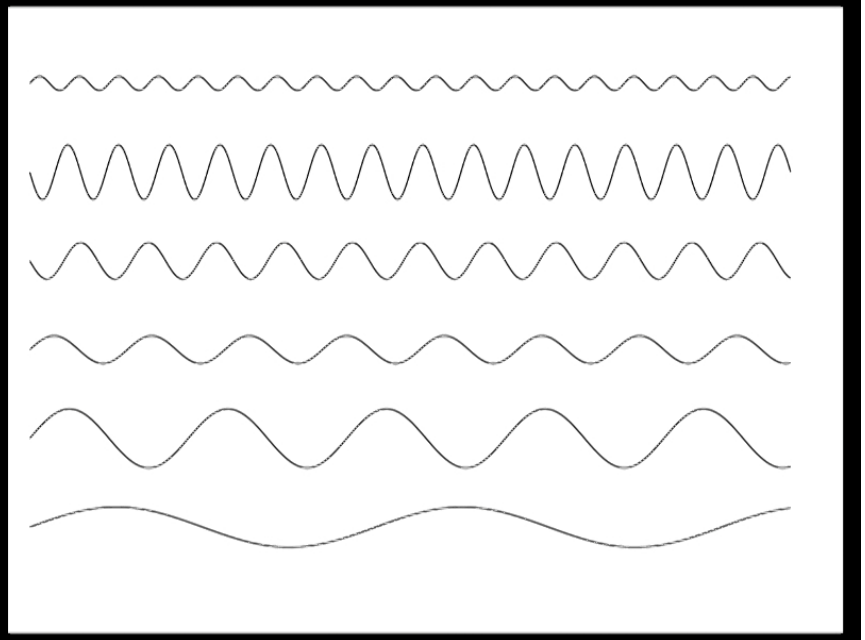


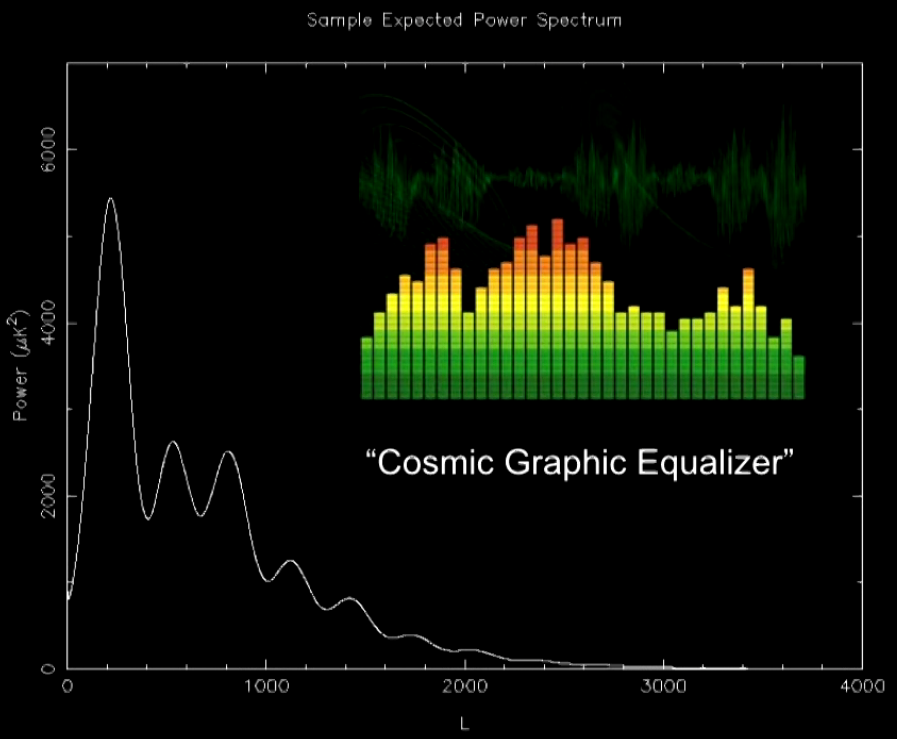


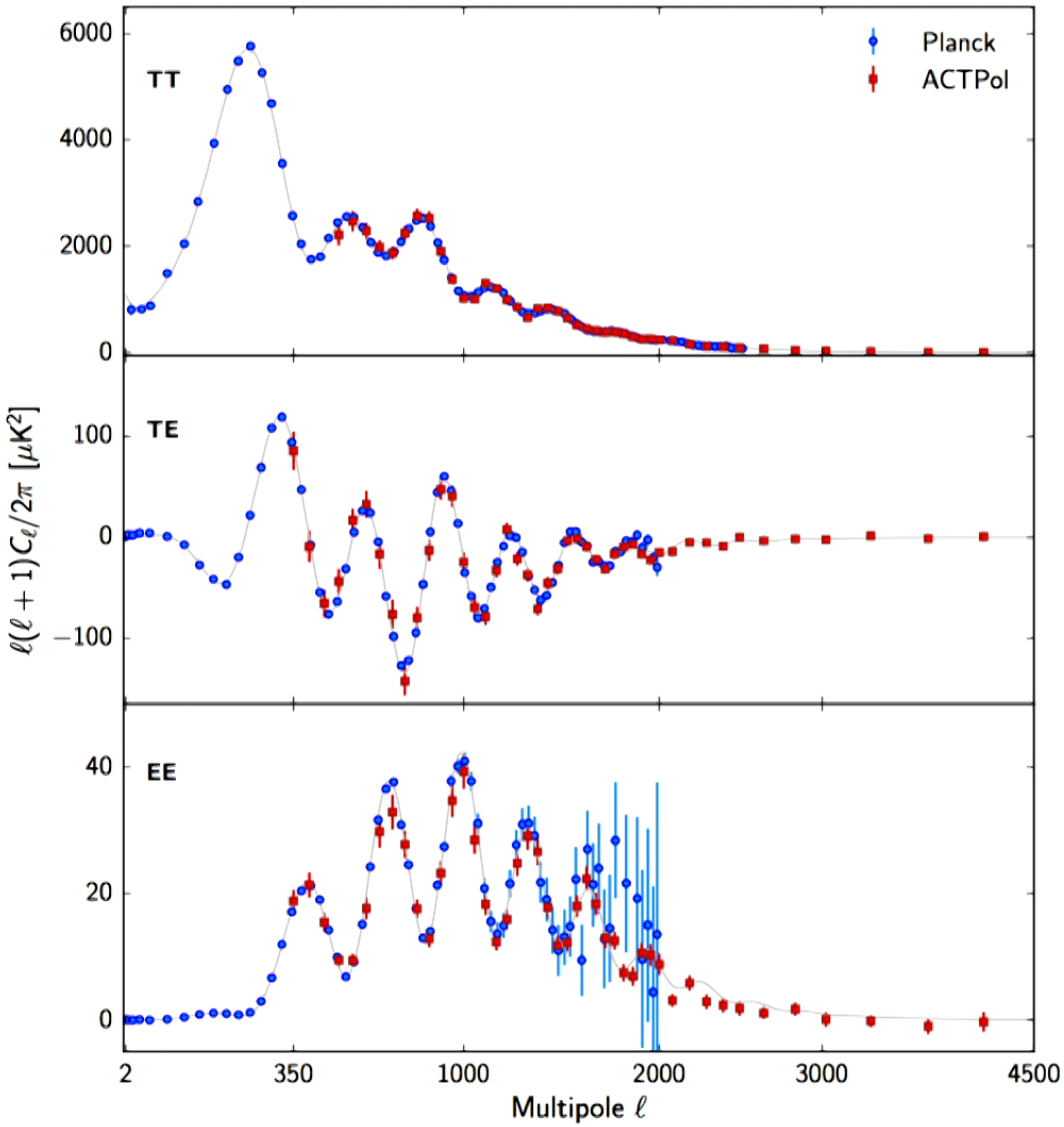
Wave Amplitudes vs. Wavelength (Power Spectrum)

Plot mean variance of waves vs. *k* to get power spectrum. Physics affects details of peaks, underlying slope. Full sky means spherical harmonics: *k*➔*l*.

Axes: Horizontal is *l*, full moon is *l*~400. Vertical is variance of Fourier modes in μK^2 (scaled by $l(l+1)/2\pi$).

This is space in which data and theory are compared.

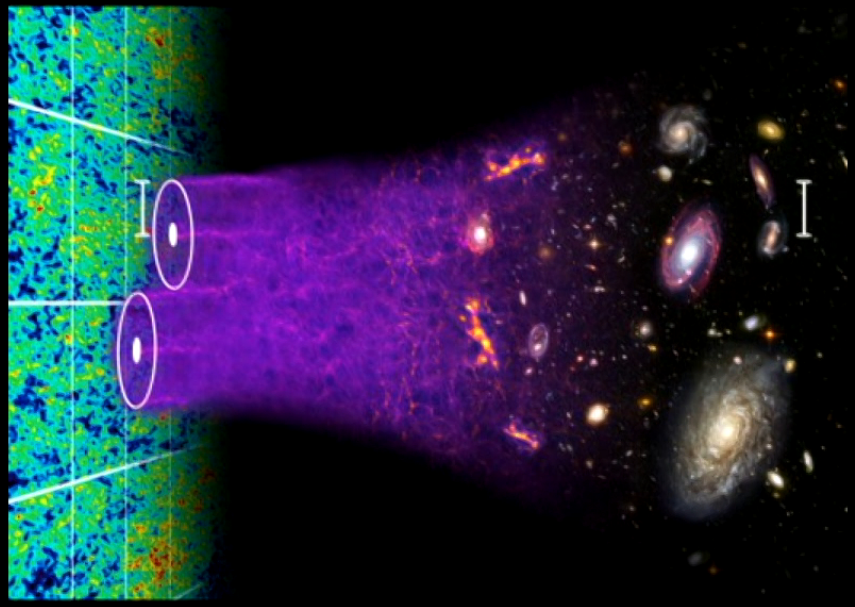




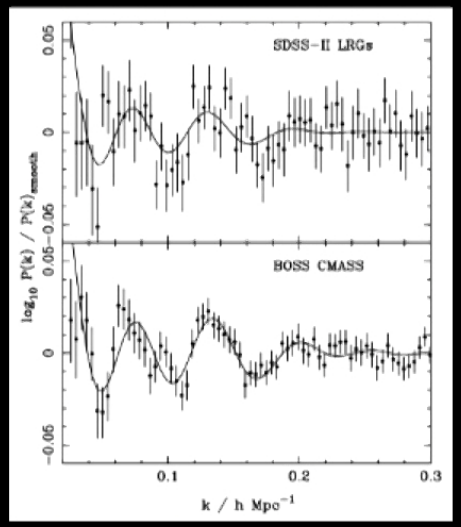
Spectrum from only 1/6 of our (ACTPol) data!

Louis et al. 2016
astro-ph/1610.02360

Galaxy Positions Should Remember This



Should see rings of correlation in galaxy positions. Measure galaxy positions and should see ripples. Below: SDSS galaxy power spectrum (images courtesy SDSS).

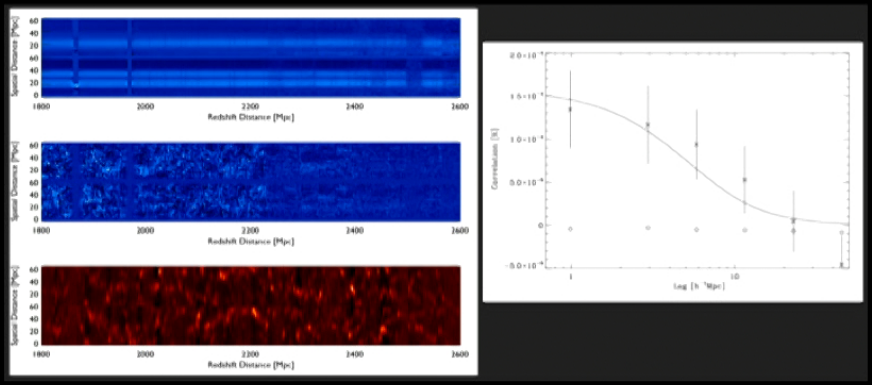


Baryon Acoustic Oscillations

- Recombination freezes in ripples in baryon density, called Baryon Acoustic Oscillations (BAOs).
- Comoving size the sound horizon at recombination. Know how to calculate apparent size given cosmology, redshift.
- BAO scale large - >100 Mpc. c.f. entire volume of universe within z=0.1 only order 10^2 BAO volumes.
- To do precision cosmology, need lots of volume: large sky area, big redshift range.

Intensity Mapping

- Would like to have large spectroscopic survey.
- Have ~10^5 L_* galaxies/BAO volume - individual galaxies not that important.
- Hydrogen 21 cm line can be used. Very faint per galaxy.
- Instead, stack up signal from many galaxies with low resolution survey.
- First detection made comparing HI maps to galaxy maps, Chang et al.



First intensity mapping detection, Chang et al.

HIRAX

- We would like to measure dark energy via intensity mapping.
- Natural design: smallish dishes (6m) at z~1 (~700 MHz). Too high, no DE effects. Too low, no volume.
- BAO signal faint, need lots of elements to reach sensitivity.
- Significant development for CHIME (Canadian cylinder BAO experiment), digital electronics basically identical.
- HIRAX supported by UKZN as part of NRF Institutional Engagement and Partnership Development.

HIRAX

- We would l
- Natural des high, no DE effects. Too
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- HIRAX sup gement and Partnership

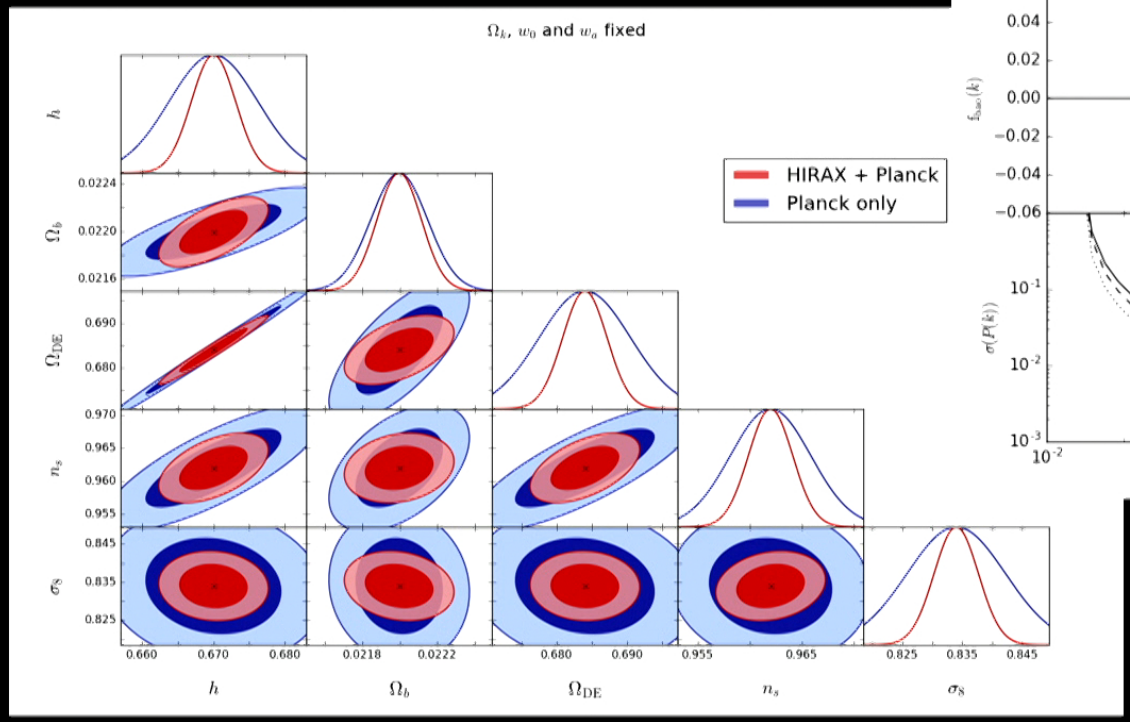
Current Design Plan

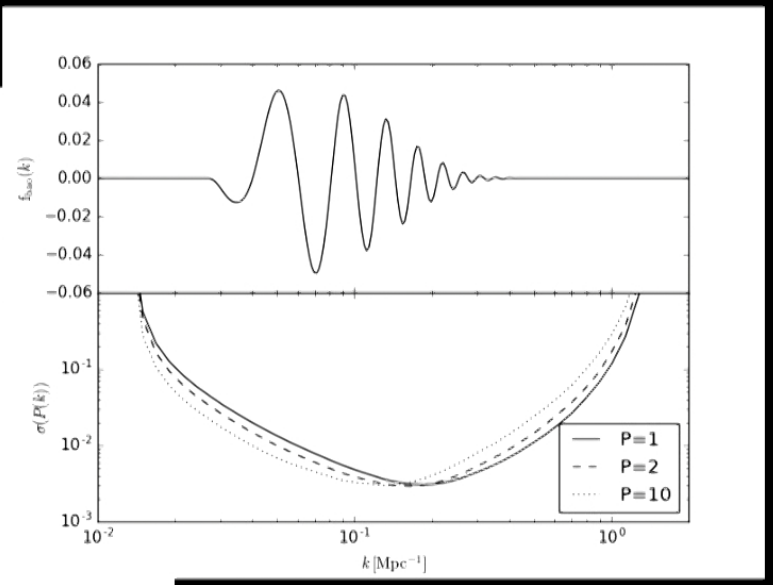
- Order 10^3 close-packed 6m dishes.
- Operate between 400-800 MHz
- Channelizing on FPGA ICE boards (McGill/Matt Dobbs)
- Correlation on GPUs (Toronto/Keith Vanderlinde).
- Dishes tilt N/S: when "deep enough" on a strip, tilt over to increase f_{sky}.
- Will beamform in correlator, for FRBs, kick out small subset of beams (~20) to external processing for pulsar search/monitoring, HI absorbers…

CHIME Comparison

- CHIME is cylinders, HIRAX will be small dishes. *Different systematics*.
- Full HIRAX will have ~3x the collecting area.
- CHIME sees the whole sky every day.
- HIRAX in the south - good for pulsars, cosmology results can be combined.
- Electronics nearly identical (beamformer will be different)
- Happy first light to CHIME! Official ceremony a few days ago.

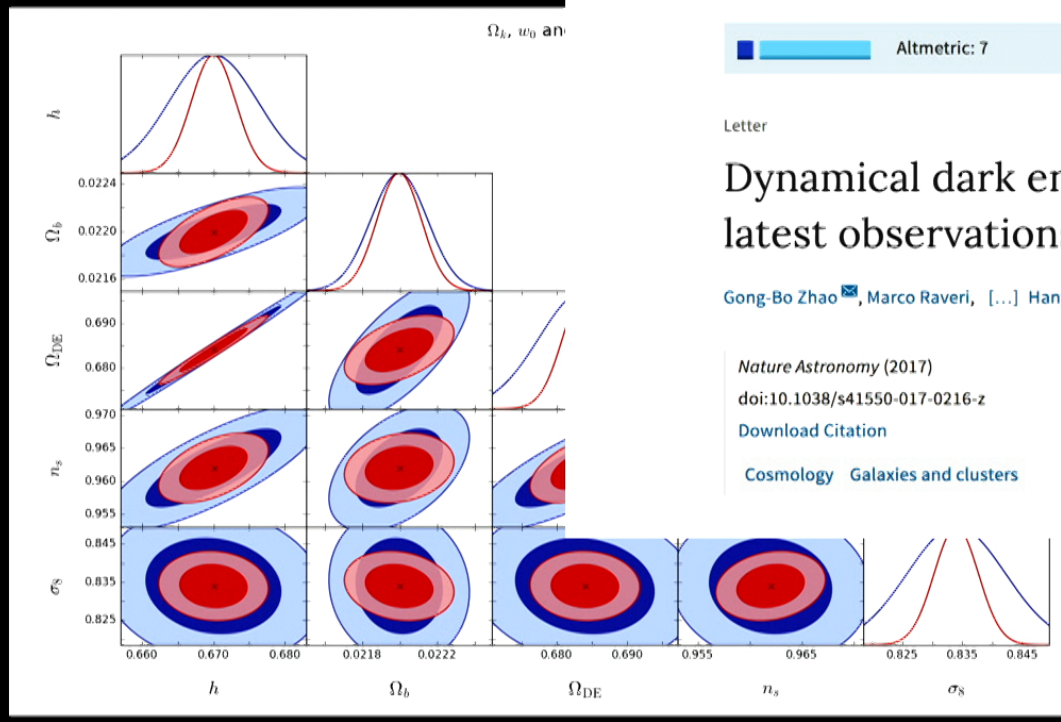
HIRAX will improve our understanding of the universe (forecasts: Amadeus Witzemann and Mario Santos)





1024 element for 4 years DE FOM ~300

HIRAX will improve our understanding of the universe (forecasts: Amadeus Witzemann and Mario Santos)



MENU

nature astronomy

Altmetric: 7 More detail »

Letter

Dynamical dark energy in light of the latest observations

Gong-Bo Zhao ✉, Marco Raveri, […] Hanyu Zhang

Nature Astronomy (2017)
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Download Citation

Cosmology Galaxies and clusters

Received: 03 March 2017
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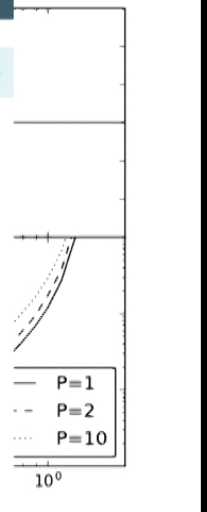
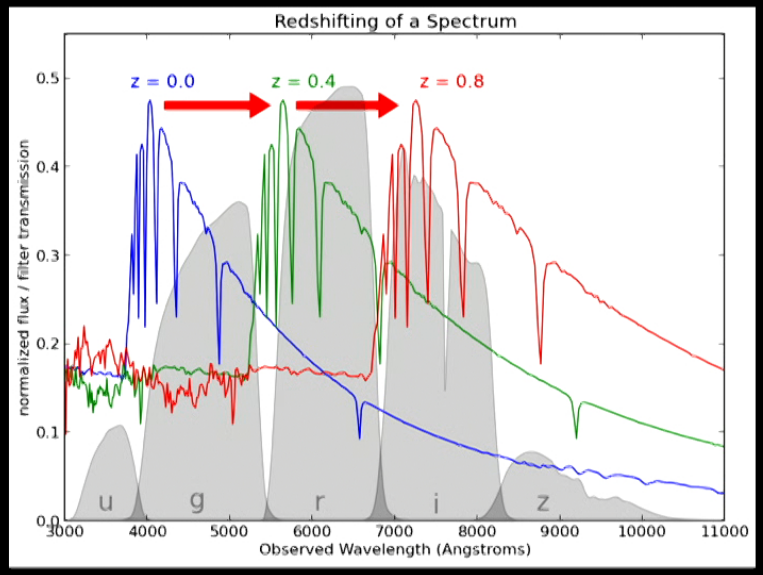
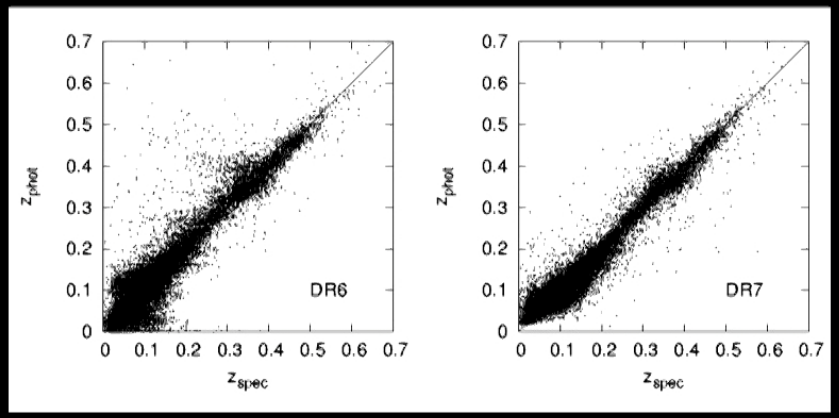


1024 element for 4 years DE FOM ~300

Redshift Catalog

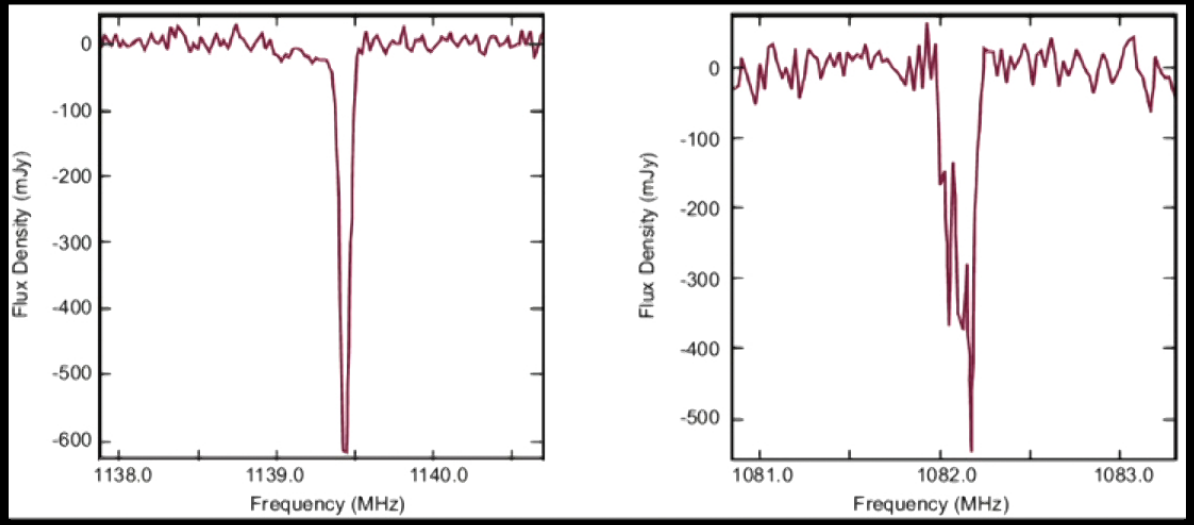
- New photometric surveys (e.g. DES, LSST…) will have many new populations of sources/need spectroscopic calibration.
- Essential to get redshift distributions to understand physics/calibrate photo-z's etc.
- HIRAX spectroscopically traces matter field. Unknown population can get biased redshift distribution by cross-correlating w/ HIRAX.
- See Alonso et al. for improvement on LSST lensing using HIRAX for photo-z calibration…





Neutral Hydrogen Absorbers

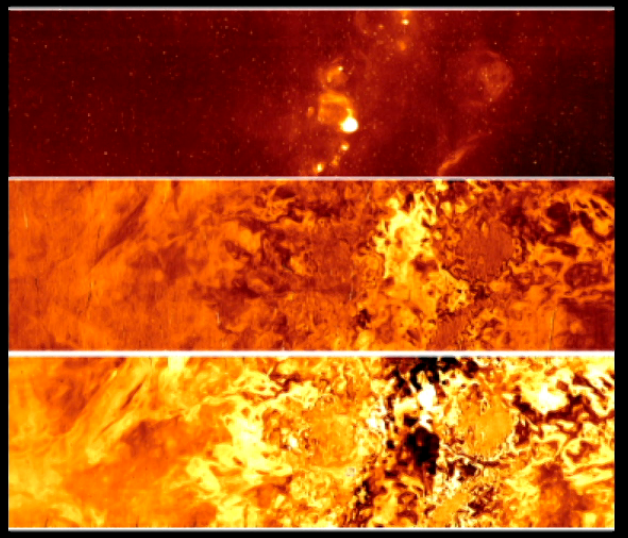
- Sometimes neutral hydrogen systems in QSO lines of sight
- Measure optical depth, line width etc. Goal is to get to physical conditions of star-forming(?) galaxies.
- Kick out beams on QSO's - restore baseband, re-channelize to get high (km/s) frequency resolution.



2 Absorbers in PKS 1413+135 (fig. courtesy NRAO)

Galactic Polarization

- Will get (whether we like it or not) very high SNR map of polarized galactic emission.
- Complements GALFACTS survey from Arecibo. HIRAX will cover galactic center. Get things like Faraday depth for studies of galactic magnetic fields.

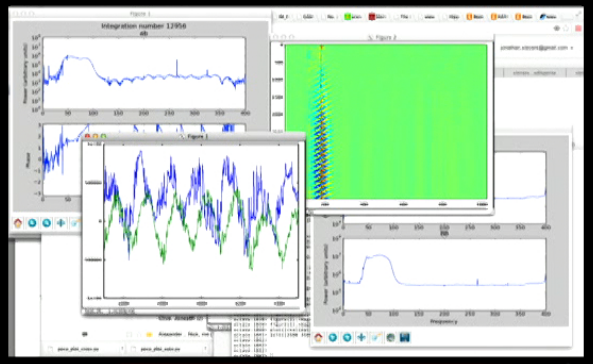


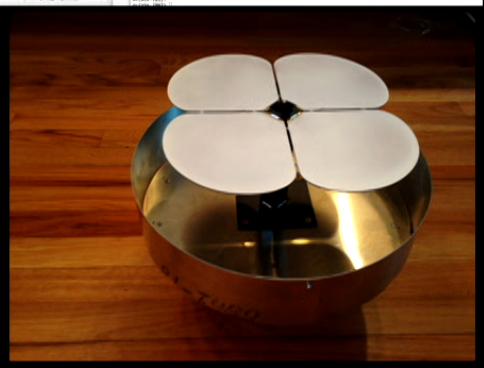
Proto-proto-prototype

Borrowed travelling ROACH board, went to DUT to build 2-element interferometer with Chiang, Peterson, Van Vuuren, Macpherson.

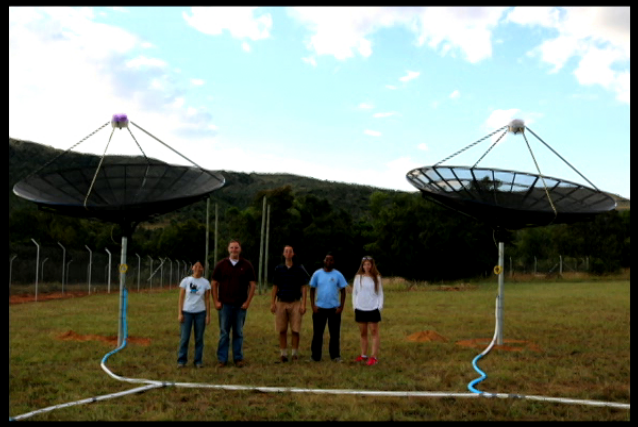
With Installed dishes on roof, cabled everything up through RF chain. Got fringes on sun within 24 hours - first in KZN!

Clockwise, bottom left:
Dish w/ team, including SKA MSc stdents Allotey, Sengate
Inside DUT control rom
First fringes!
Prototype HIRAX feed





4-Dish Installation outside Johannesburg



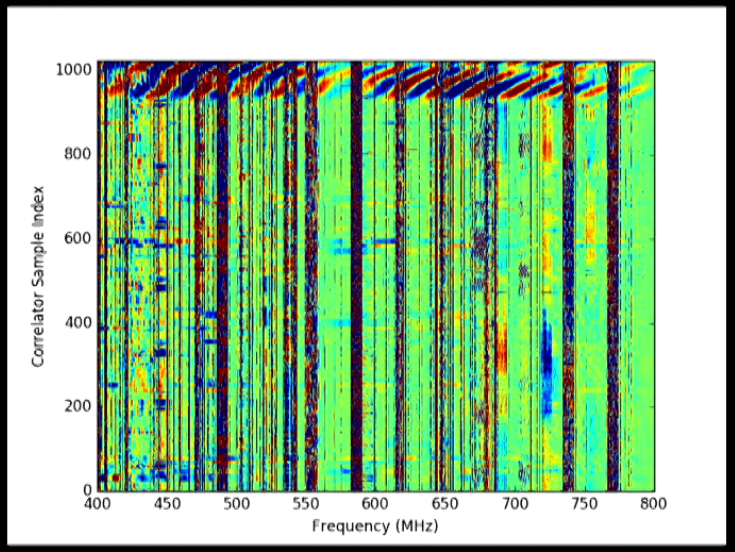
8 Dish Installation

HartRAO technician Andrew Masiteng, UKZN PhD student Onkabetse Sengate and UKZN MSc student Kabelo Kesebonye assemble 6m dish

Top Middle: Yale student Emily Kuhn and HartRAO technician Jacques Grobler Install feeds.
Top Right: Onkabetse Sengate, Nivek Ghazi and Cynthia Chiang work on RFI testing, while Austin Gumba works on RF over fibre.
Right: Sievers, UKZN Postdoc Ben Saliwanchick, Carnegie-Mellon Professor Jeff Peterson pose with just-assembled dish.

Current

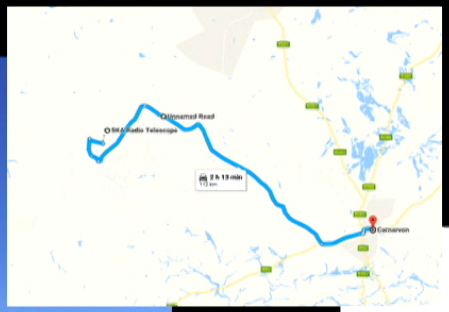
Five dishes fully instrumented, waiting on feeds for the rest (September)

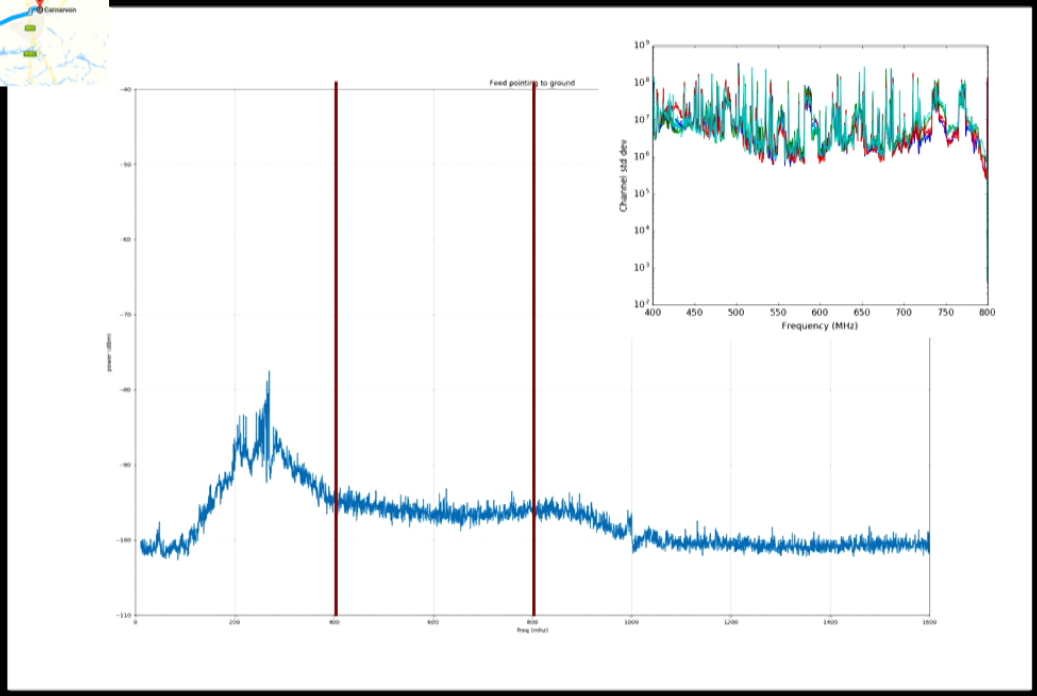


3 hours of data from 1 pair of antennas

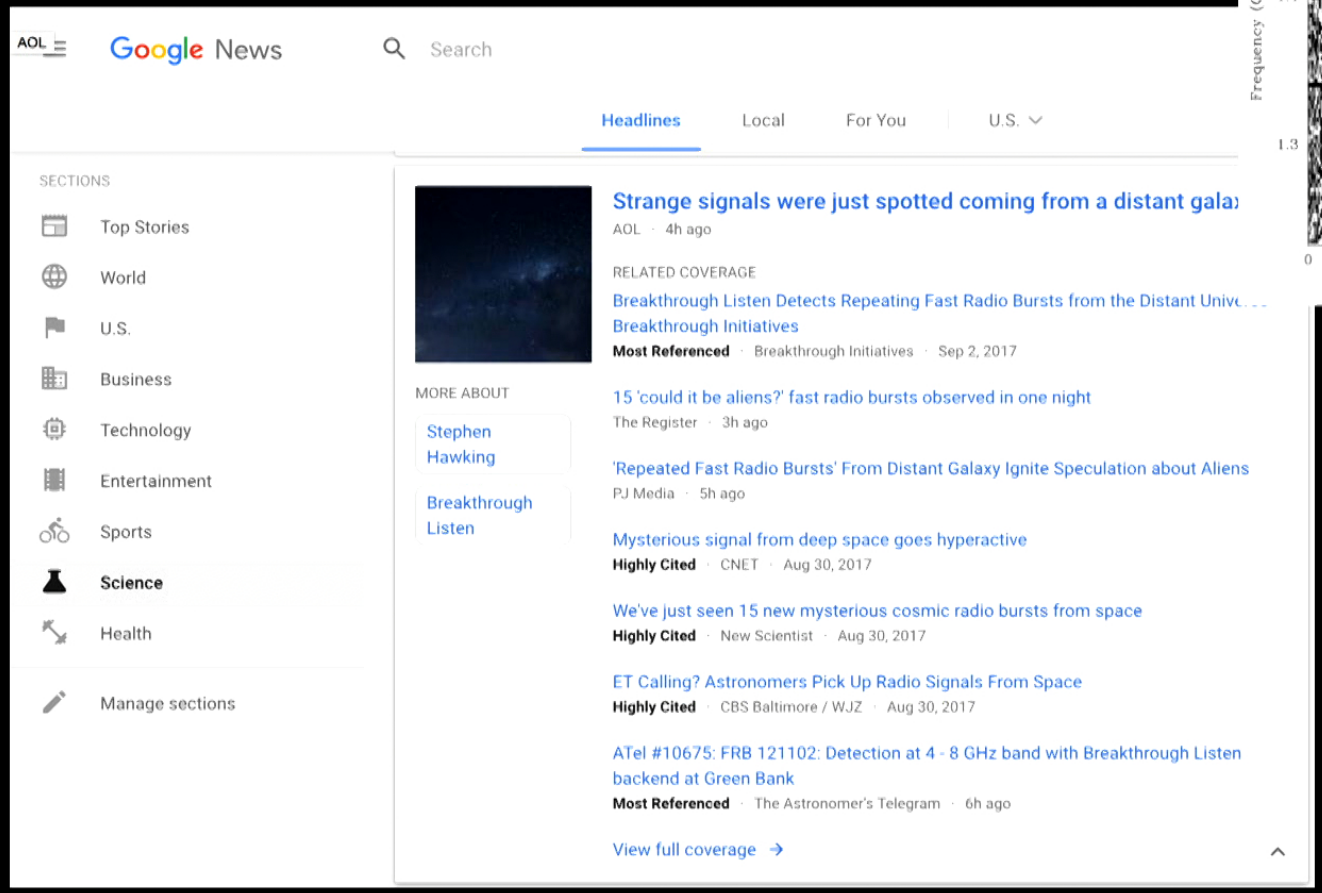
Site Test w/Feed

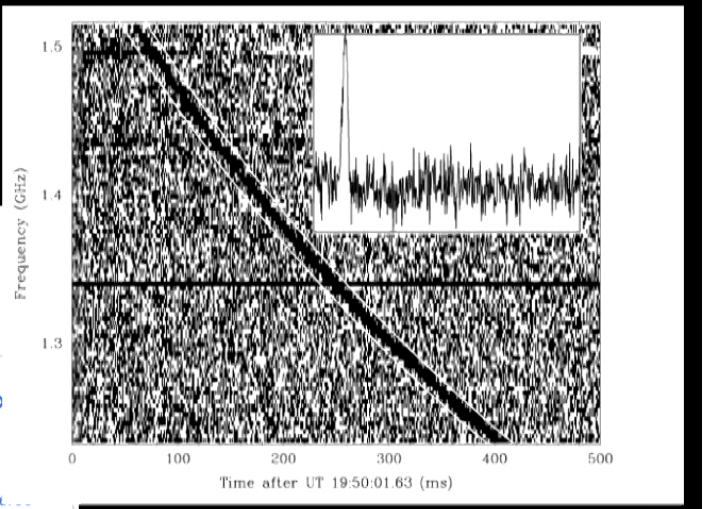
Jeff Peterson at HIRAX site in Karoo. Conditions look spectacular! (Inset - interference at HartRAO)





Fast Radio Bursts





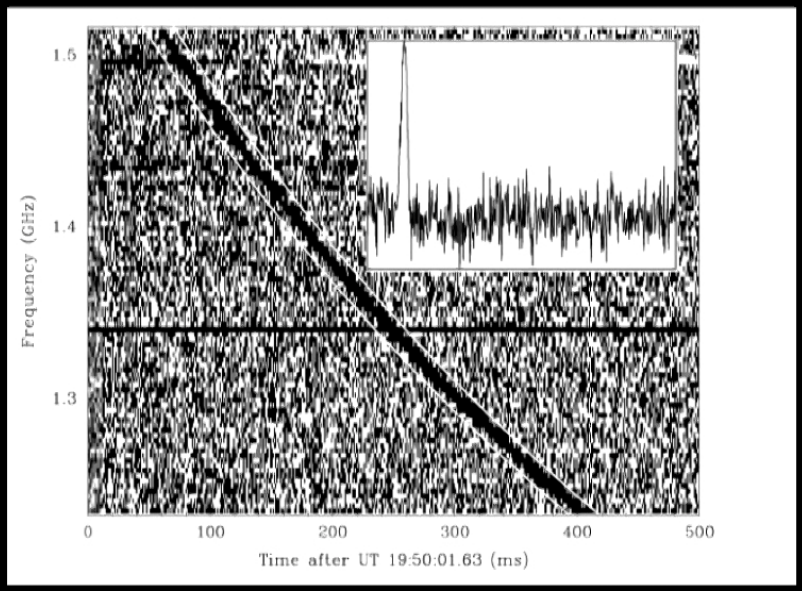
FRBs are mysterious bursts discovered a decade ago, and remain unexplained.

HIRAX will be *the* premiere instrument.

HIRAX & Pulsars/FRB

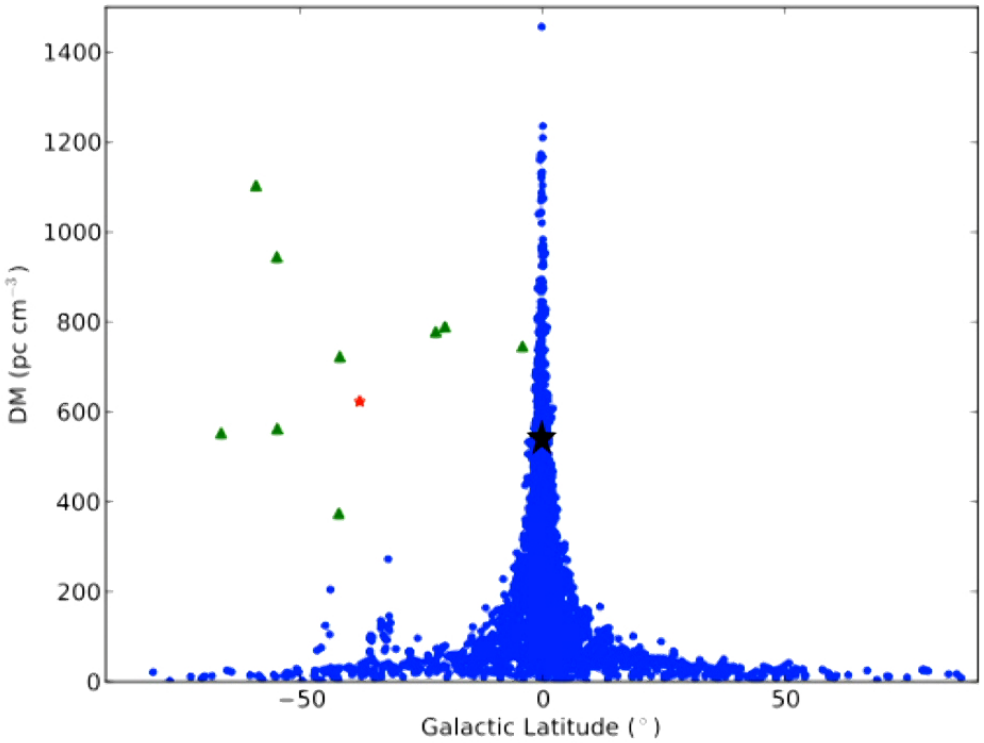
- At nominal sensitivity, get to ~12 μJy/beam/day (RMS).
- Need to search ~couple dozen beams simultaneously to cover full survey (approx 15,000 square degrees) once. Correlator will upres frequency before sending to FRB/pulsar back ends.
- Full survey ~1 μJy/beam. What needs to be saved to maximize science? Will have ~1000 channels, search for stacked slow pulsars?
- Fantastic FRB machine. For Euclidean counts, event rate proportional to dish diameter times # of beams, so should have ~500x Parkes rate.

Dispersion



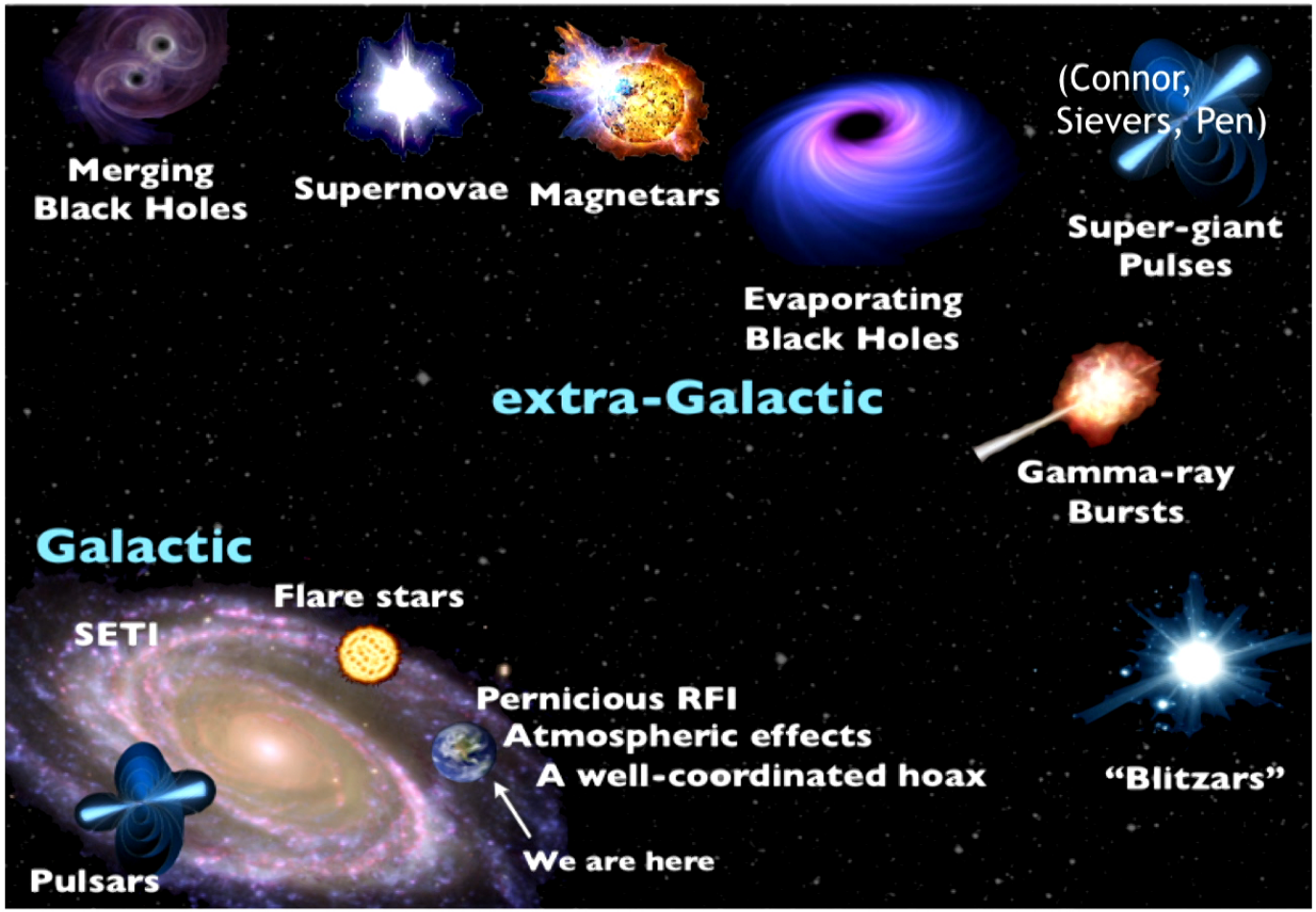
- Electrons slow down light as it travels.
- The more electrons, the more slowing happens
- The lower the frequency, the more slowing.
- Total delay in seconds = 4150*DM/ ν^2, ν in MHz.
- DM=*Dispersion Measure*. It is total electron column density (in pc/ cm^3, so DM=1 is 1 electron/cm^3 over 1 parsec)
- If you like optical depth from Thomson scattering, τ~DM/500,000

FRB sources are very likely outside of the Milky Way



Blue: pulsar
Green: FRB
Red: FRB110523
Black: repeater

FRB proposed models



Slide by J Hessels

False positive events at Parkes due to Microwave oven (perytons)

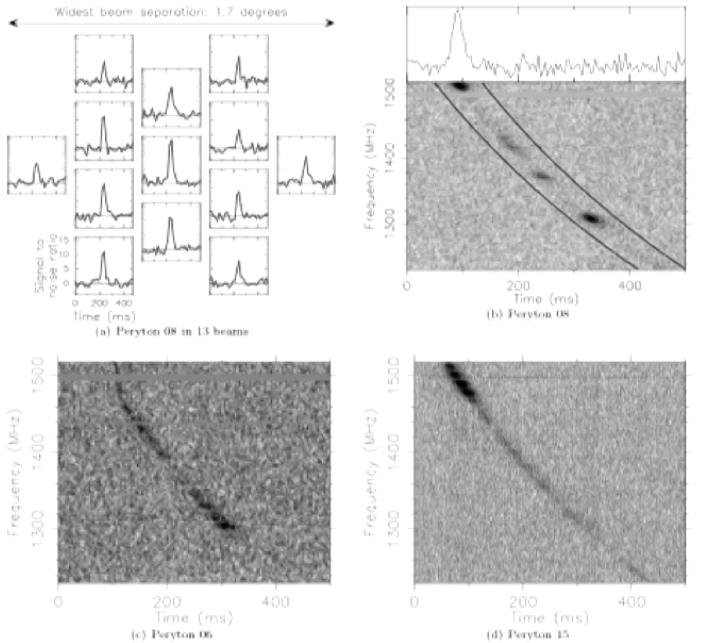
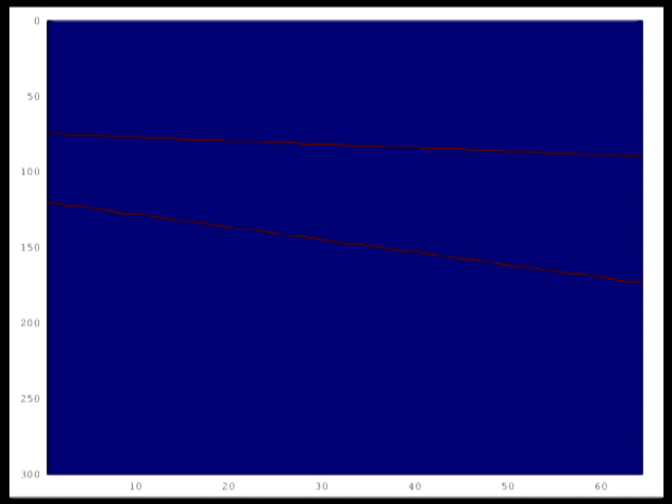


Fig. 1.— Spectrograms and time series for several detections. **(b,c,d)** Data from the 13 beams have been summed to enhance the signal. Frequency channels with known interference have been blanked. **(a)**, De-dispersed time series showing Peryton 08 in the 13-beam multibeam receiver as the beams are distributed on the sky. **(b)** De-dispersed time series and spectrogram of Peryton 08. The black lines trace the best-fit dispersive delay for this detection. **(c,d)** Spectrograms of Peryton 06 and 15, respectively.

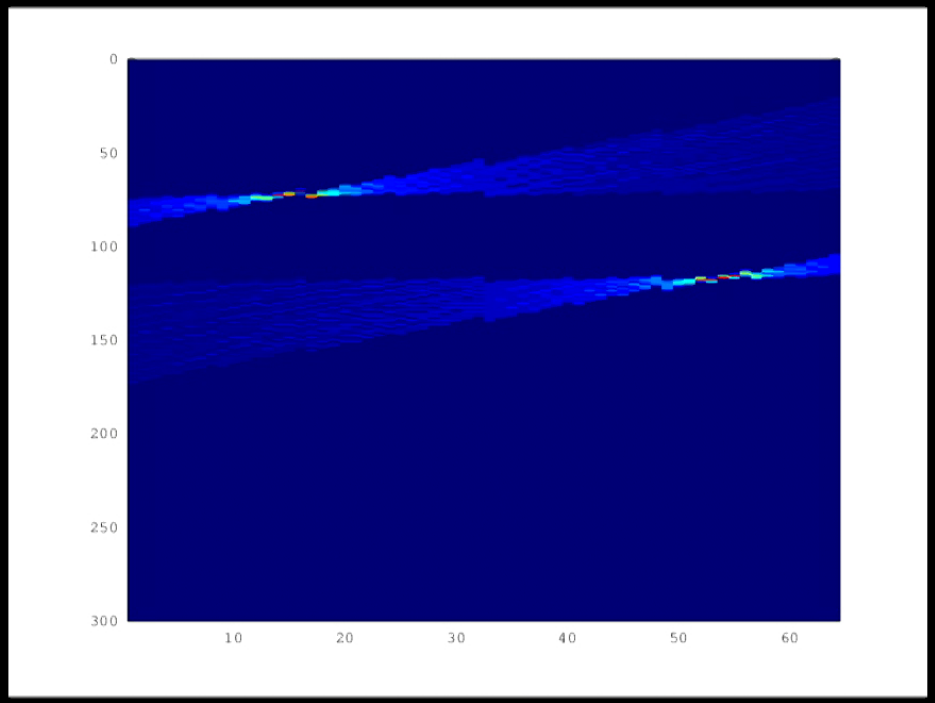
DM Transform



To search for FRBs, need to search over *all* arrival times and *all* DMs FFT-type transform works for this on HIRAX scale.

(K. Smith on this for CHIME)

t_{burst} ↓



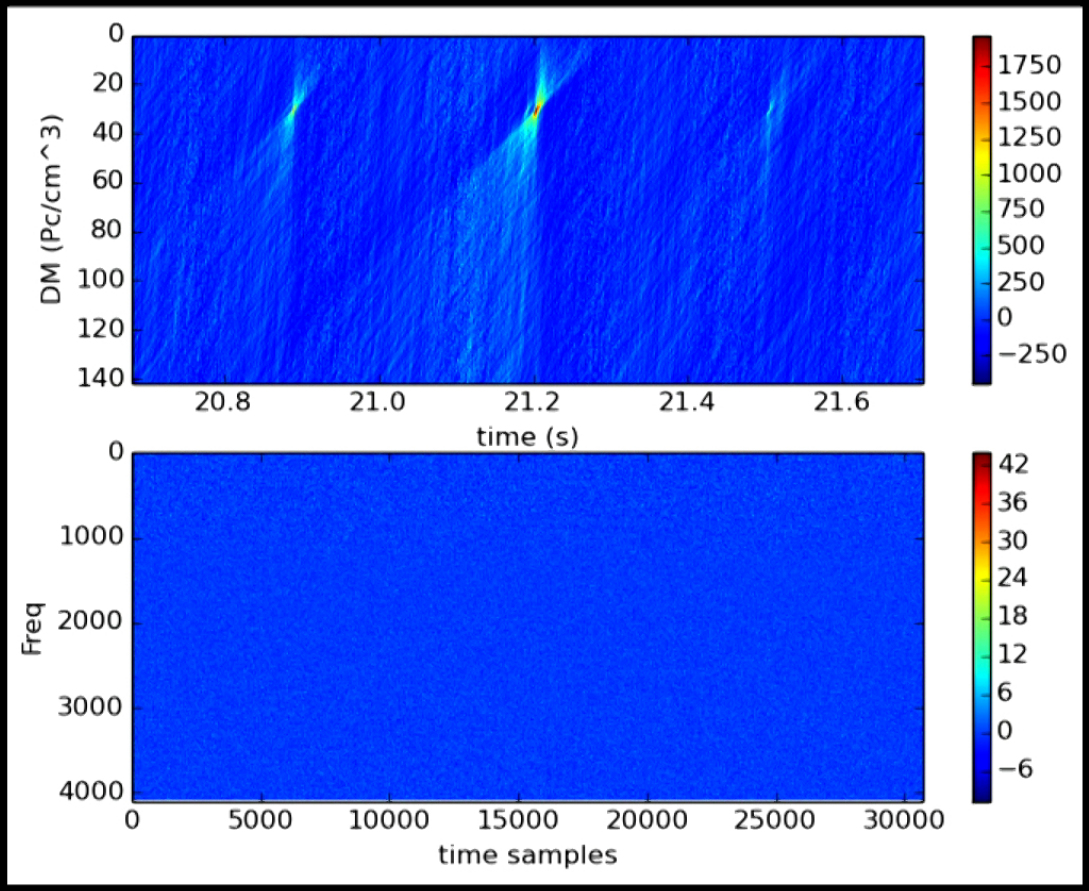
DM →

GBT FRB Search

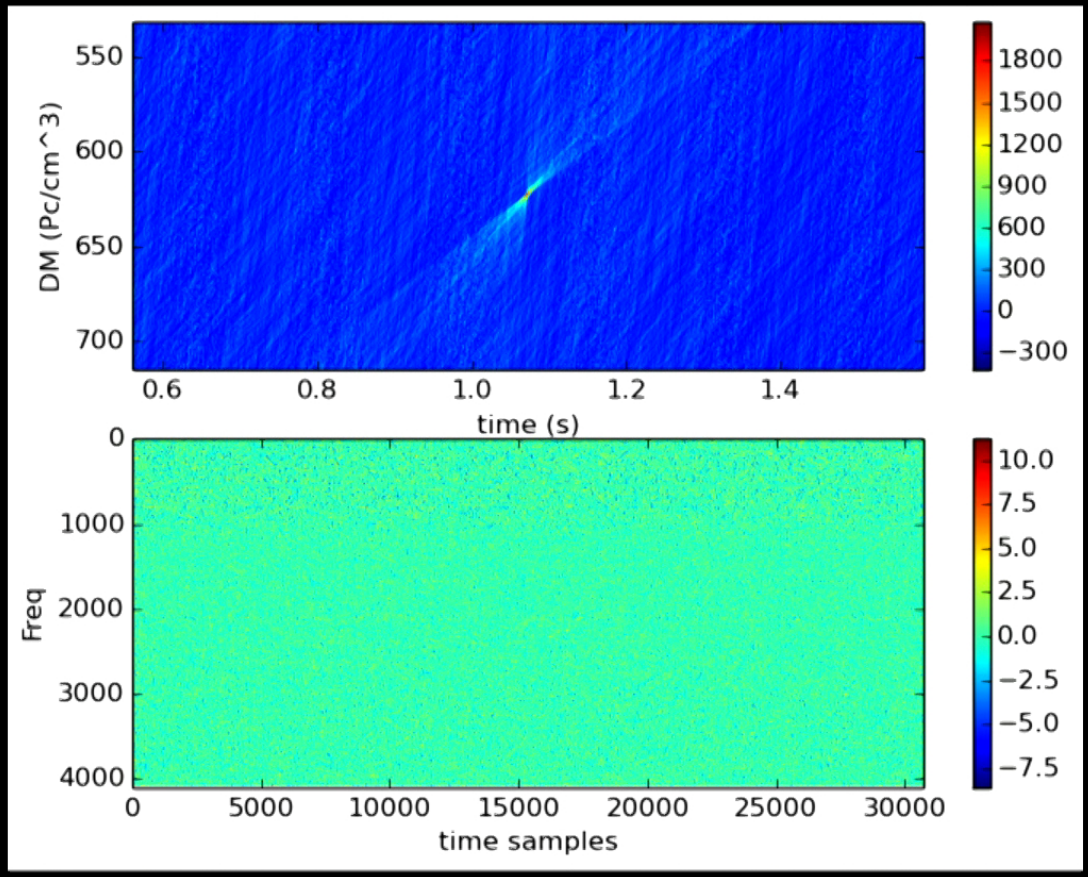
•With new expts in mind, developed new pipeline for searching. Tested on GBT archival data.

•650 Hours
•Frequency 700 to 900 MHz
•Spectra recorded every 1.024 ms
•15 arcminute angular resolution
•NB - telescope scanning during data collection

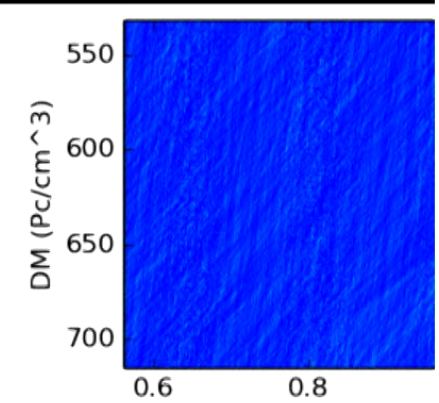
Scanning Across Known Pulsar

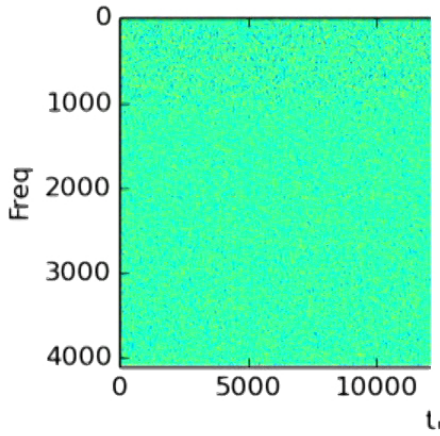


FRB w/ GBT

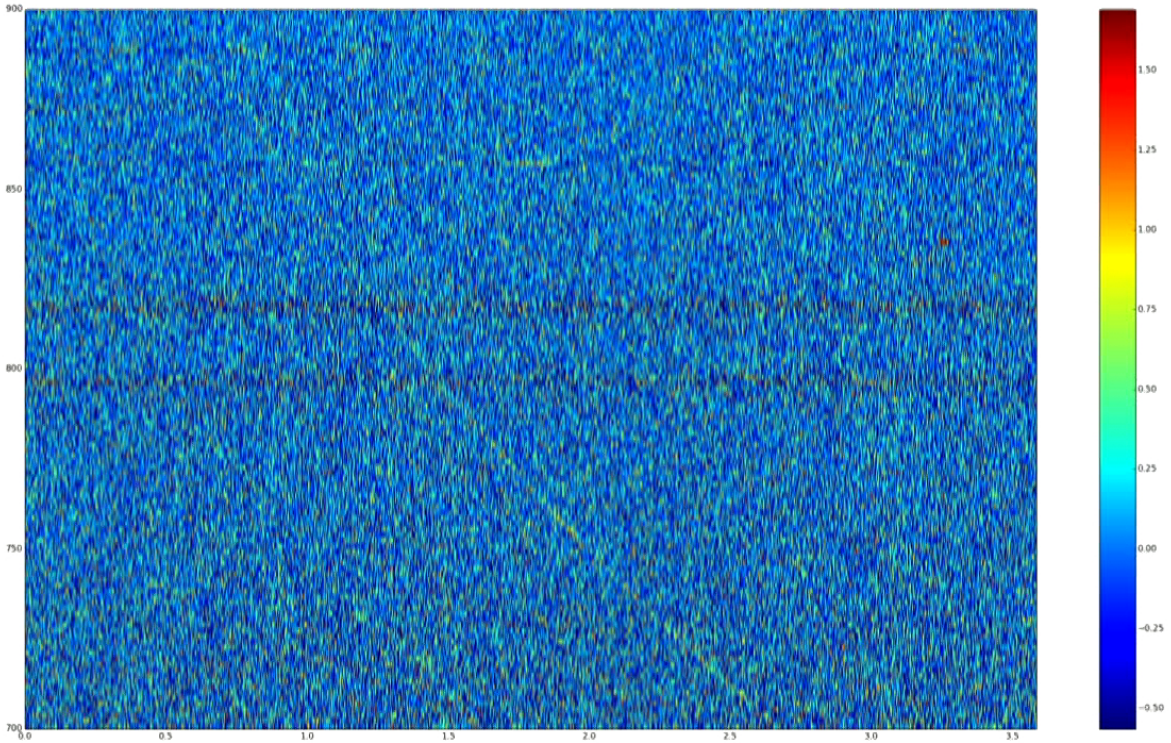

DM (Pc/cm^3)
550
600
650
700
0.6
0.8
1.0
1.2
1.4
time (s)
1800
1500
1200
900
600
300
0
−300
Freq
0
1000
2000
3000
4000
0
5000
10000
15000
20000
25000
30000
time samples
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5

FRB w/ GBT

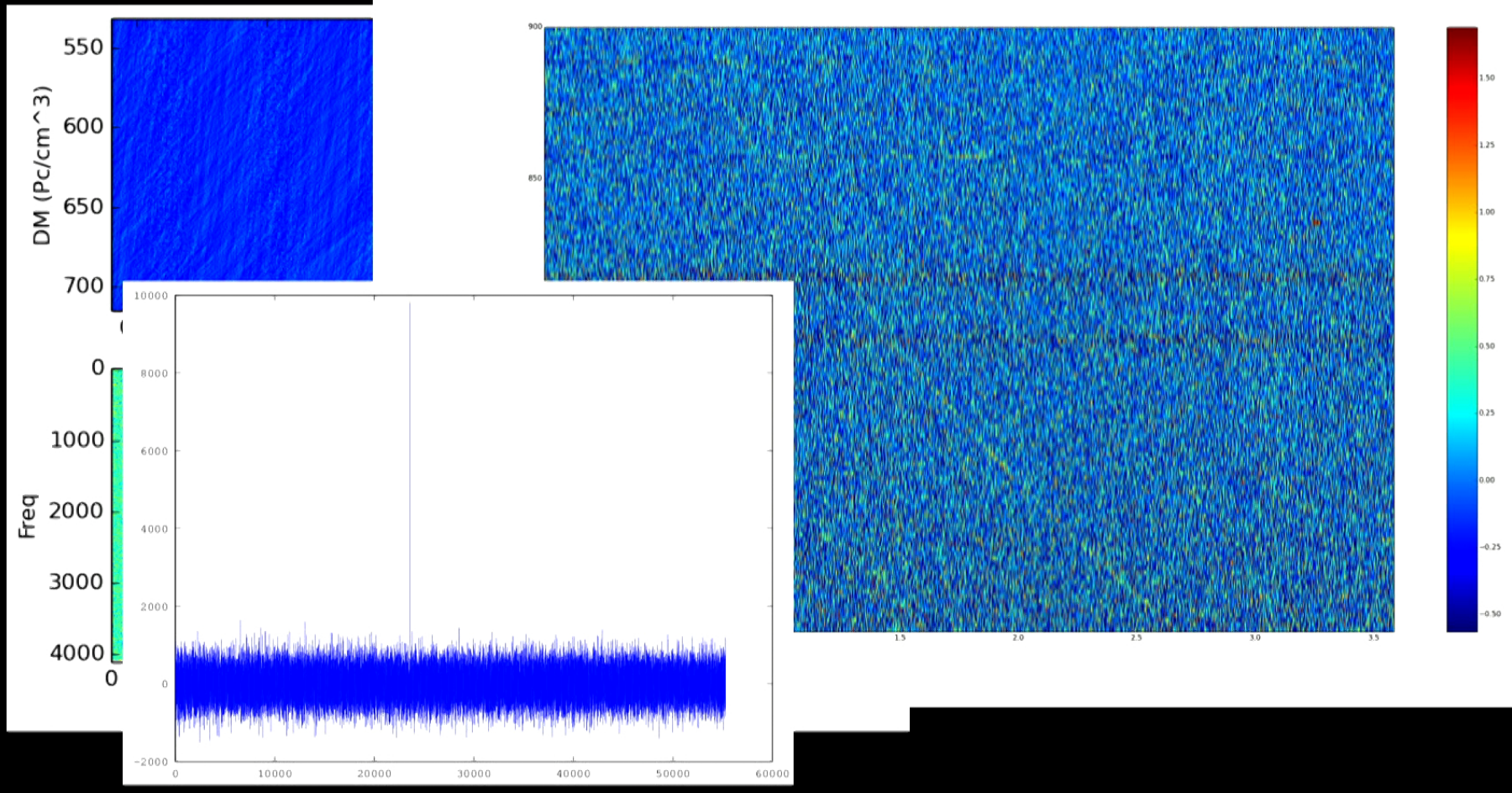


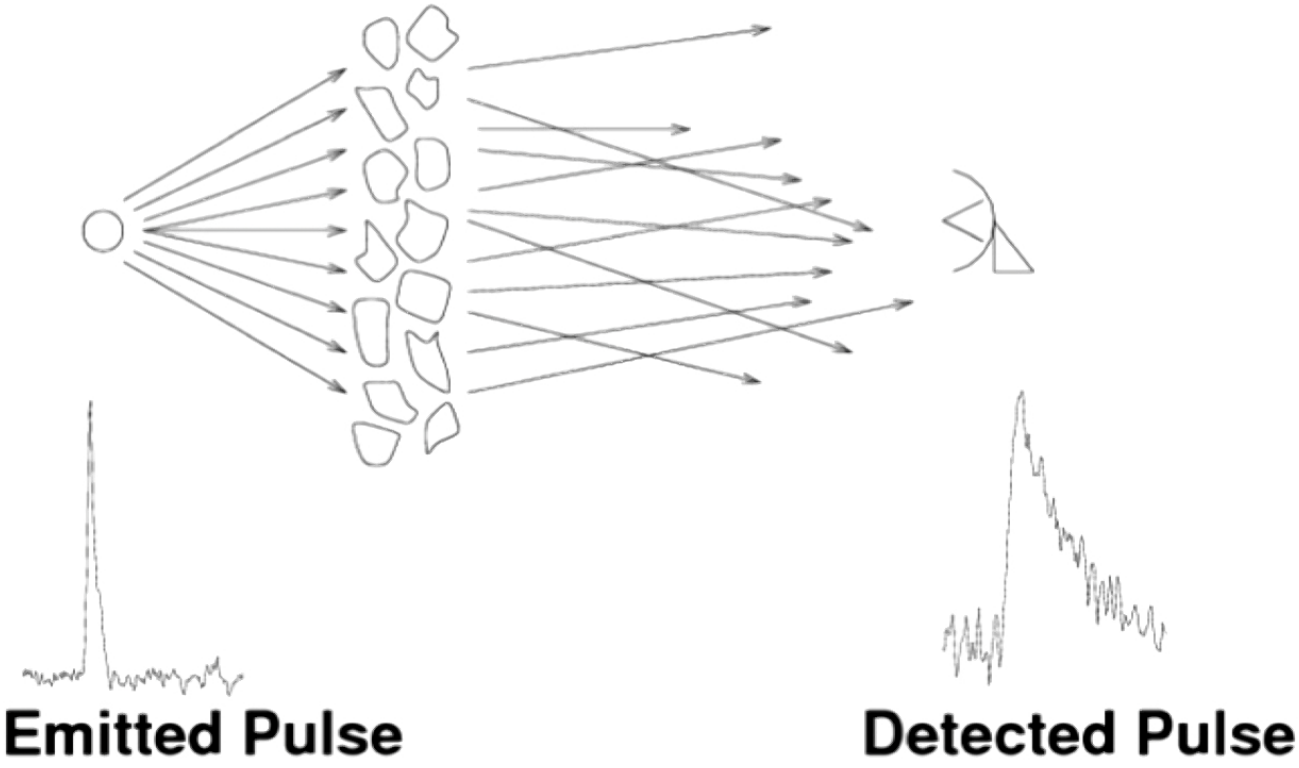


time samples

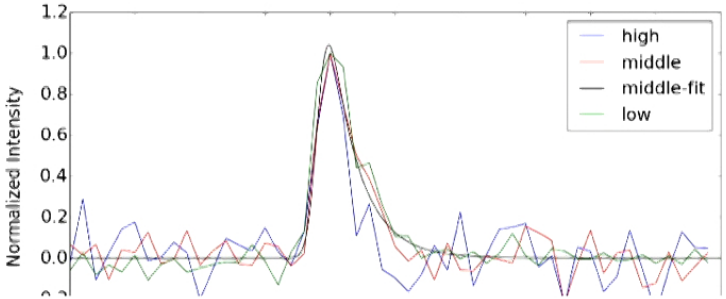


FRB w/ GBT

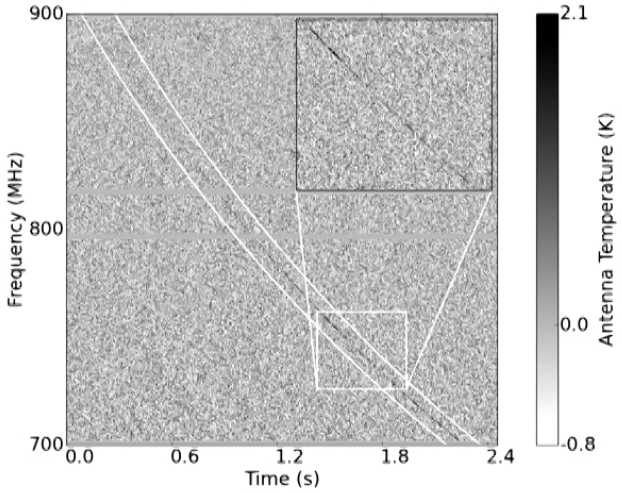

DM (Pc/cm^3)
550
600
650
700
Freq
0
1000
2000
3000
4000
900
850
1.5
2.0
2.5
3.0
3.5
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
10000
8000
6000
4000
2000
0
−2000
0
10000
20000
30000
40000
50000
60000


Emitted Pulse
Detected Pulse

Scattering and Scintillation detected

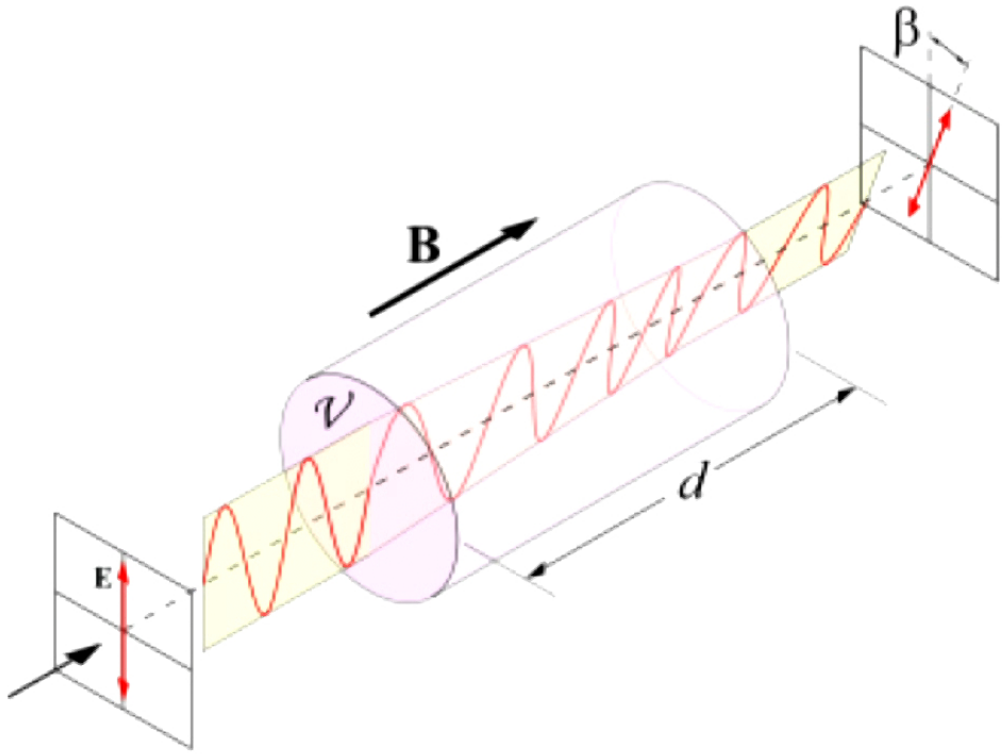


Scattering: multi-path reflection from ISM. Probably extragalactic.

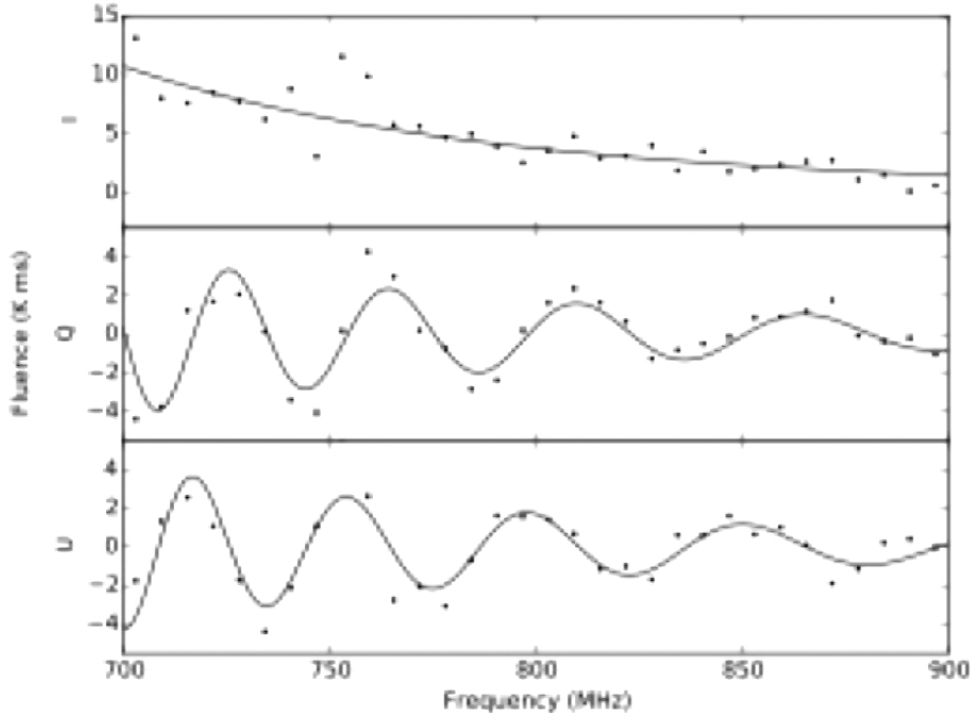


Scintillation: coherent multi-path from ISM. Probably galactic (similar to nearby pulsar)

Faraday effect measures B along line of site



Faraday rotation also detected



Magnetization is ten times as much as Milky Way and IGM Can explain

There is almost certainly magnetized plasma at the burst.

Burst fit parameters

Barycentric $\nu = \infty$ arrival (MJD)	55704.62939511
GBT boresight at 900 MHz arrival	RA = $21^h45^m31^s$ Dec = $-00^d15^m23^s$ $l = 56.0795°$ $b = -37.9435°$
GBT boresight at 700 MHz arrival	RA = $21^h45^m12^s$ Dec = $-00^d09^m37^s$ $l = 56.1215°$ $b = -37.8234°$
Dispersion measure ($pc\,cm^{-3}$)	623.30(6)
Fluence at 800 MHz (K ms)	3.79(15)
Spectral index	−7.8(4)
Unscattered pulse FWHM (ms)	1.73(17)
Scattering time at 800 MHz (ms)	1.66(14)
Linear polarization fraction (%)	44(3)
Rotation measure (rad m^{-2})	−186.1(1.4)
Polarization rotation rate (rad ms^{-1})	−0.25(5)
Dispersion measure index	−1.998(3)
Scattering index	−3.6(1.4)
Rotation measure index	−1.7(2)

Plasma Density

- True dispersion relation is $k^2 = \omega^2 + \omega_p^2$
- At frequencies "near" plasma frequency, dispersion relation deviates from λ^2.
- Precise measurement of spectral index (-1.998±0.003) lets us plasma frequency
- Implies $n_e < 1.3e7 cm^{-3}$ (95%), minimum size of DM region 10 AU. FRB must be extragalactic.

Implications of FRB110523 data

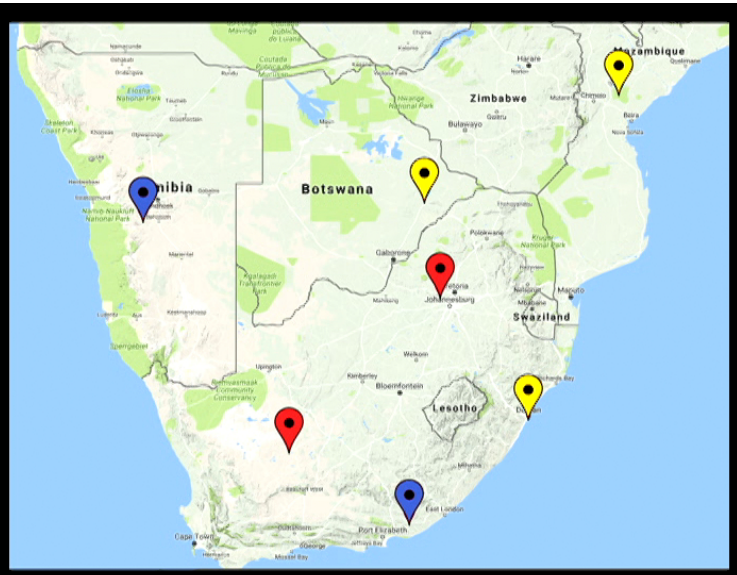
- Not caused be the Parkes Microwave oven
- Likely astronomical…all parameters fit
- Substantial material is near (<50kpc) the source, but not too near (>10 AU)
- Must understand source environment before using FRBs for cosmology.
- There are bursts at HIRAX/CHIME frequencies! (More now seen from Molonglo)

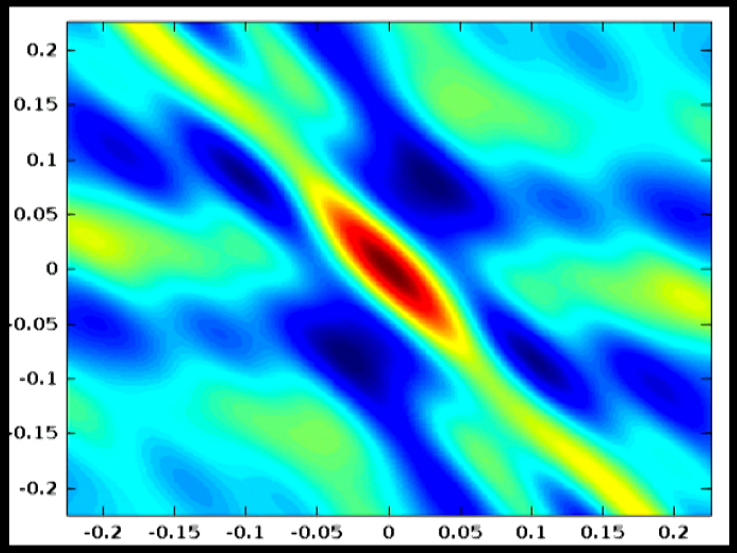
Big FRB Challenge

- Location, location, location.
- Without good (1") positions, we do not know what galaxy FRBs come from.
- With no galaxy, no redshift, hence no distance, no energy.
- Only one FRB has been seen to repeat. That has been localized, comes from z=0.19 (2.5 billion light years).
- HIRAX uniquely suited to change this.

Outriggers

- With outriggers, can get VLBI positions for HIRAX events
- 6-8 8-dish stations gives ~5 sigma detections on all 15-sigma core-detected FRBs (matching primary beams simplifies for HIRAX)
- HartRAO dishes will be one site.
- Add stations to suitable African VLBI locations. AVN interested in training.
- Outriggers store baseband for ~1-2 minutes, save/transmit when triggered.
- Each station takes ~0.5 TB of RAM per 8 dishes.





- ~1000 km baselines
- resolution ~100 mas, centroiding to few 10s of mas
- Red: funded/under construction. Yellow: proposed (Botswana, Durban)/advanced discussions (Mozambique). Blue: desirable
- Bottom: beam from red+yellow for flat-spectrum FRB. Plot axis in arcseconds (typical far away galaxy 1").
- Can get up to dozens of positions/day.

Site Testing in Botswana (last week)

- BIUST interested in hosting HIRAX outrigger station.
- Would be 8 or 16 dishes, working as a fully functioning interferometer.
- If suitable site identified could build early next year (waiting on updated dish design).
- Students involvement encouraged, both in construction and analysis.

Site Testing in Botswana (last week)

Site Testing in Botswana (last week)

FRBs as Probes of Physics

- FRBs have precise timings and precise column density measurements.
- Equivalence principle tests
- Multiply lensed FRBs (0.03" positions useful here)
- Cosmic structure - combine kSZ+FRBs?
- Might some GW events be FRBs? (HIRAX also sensitive to slow transients)

Current HIRAX Status

- Funded for 128+ elements. Looking for more.
- 8 elements built at HartRAO, feeds later this month.
- Core site will be in Karoo. Construction can start 2019Q3 (we think)
- In the interim, will try to expand HartRAO to 32 dishes, build 2-3 outrigger stations.
- HartRAO+outriggers should be enough to find ~1 FRB/month *with position*.

Summary

- HIRAX will probe dark energy through baryon acoustic oscillations.
- HIRAX will also find thousands of fast radio bursts (and pulsars)
- With outriggers, HIRAX will also find high-precision (<0.1") positions for large fraction of FRBs.
- FRBs could be a powerful probe - think of new things to do with thousands of FRBs with positions/redshifts.


Greetings from king penguins
April 12, 2017