

The Hydrogen Intensity and Real-time Analysis eXperiment

Jonathan Sievers for the HIRAX Collaboration



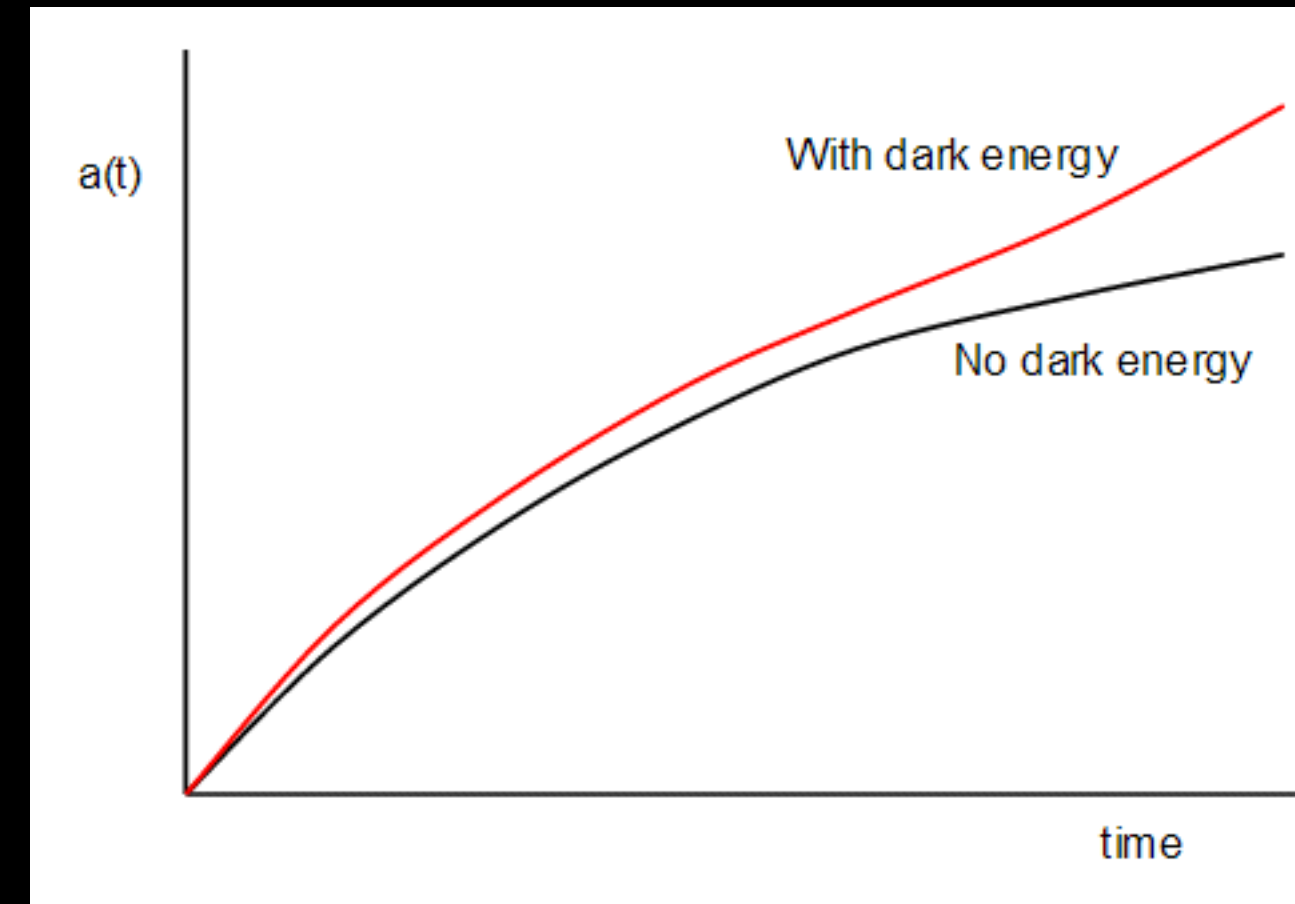
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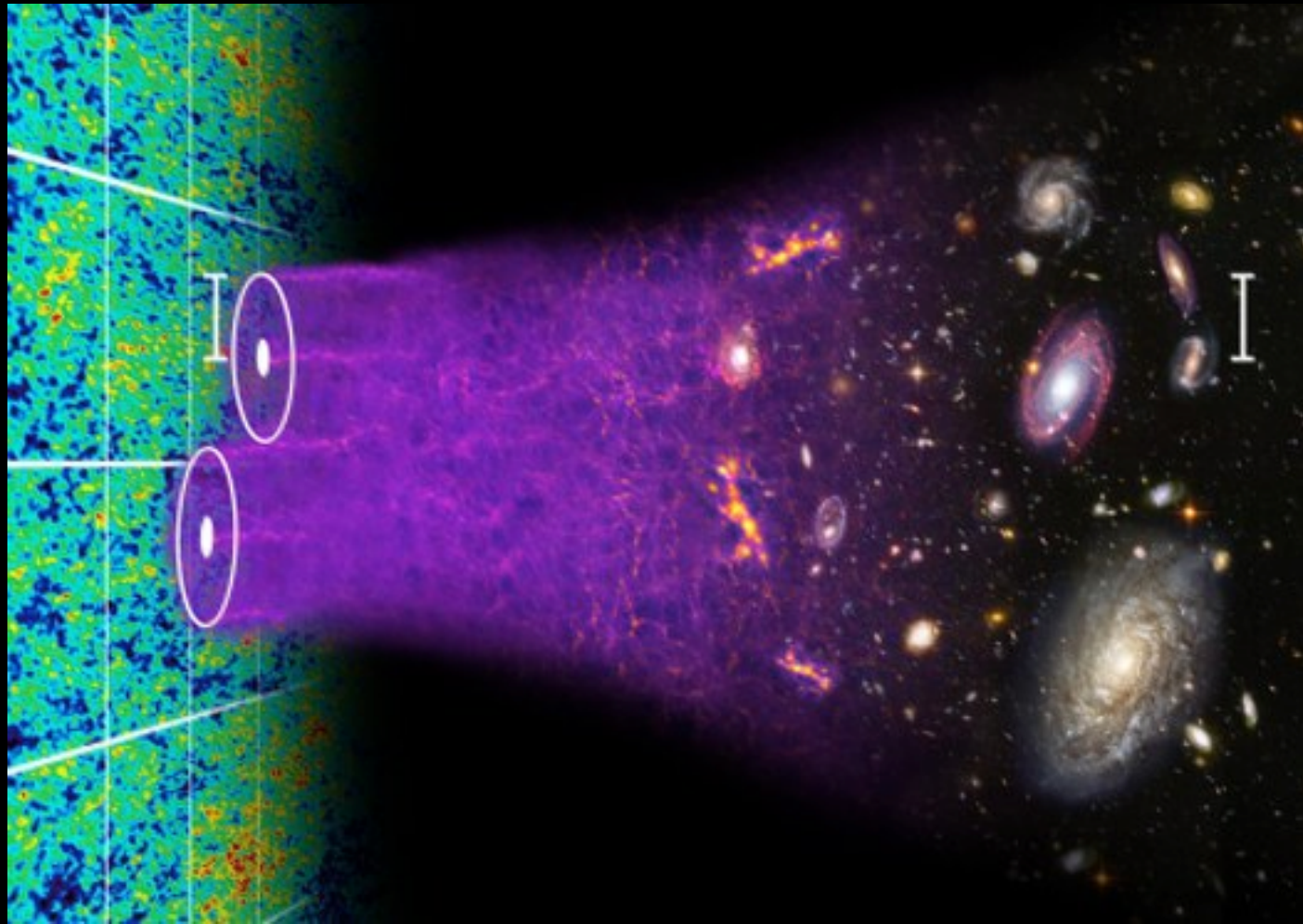
<http://www.acru.ukzn.ac.za/~hirax/>

Standard Rulers

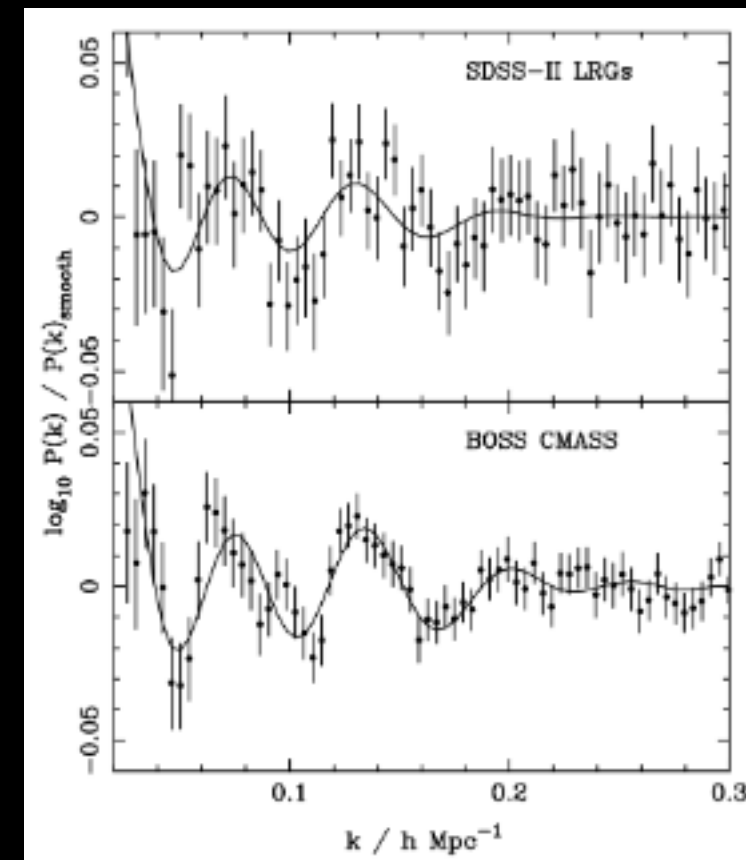
- We can use hydrogen to learn about dark energy.
- One way to measure dark energy is with standard rulers.
- Apparent size of objects of known physical size depends on dark energy.
- By tracing out size of rulers, we can describe dark energy.
- If only we had a population of things whose size we knew...



Galaxy Positions Remember The CMB Ripples



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

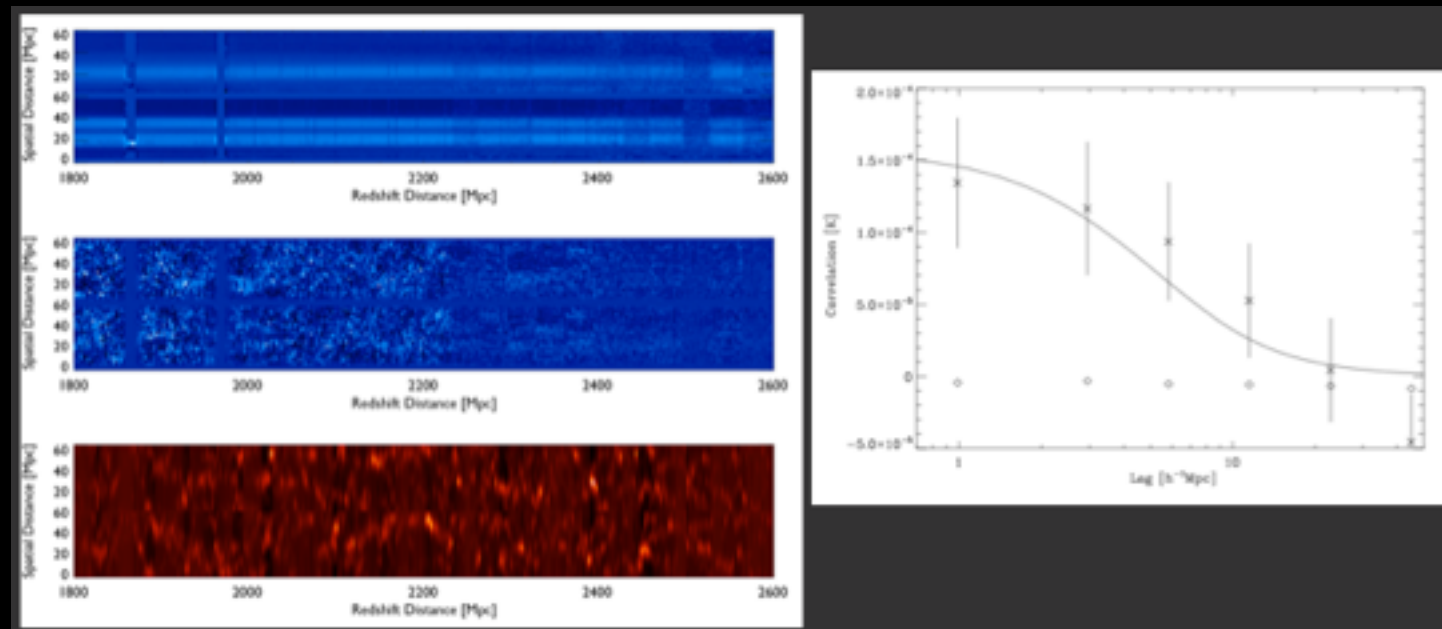


Large Volume Needed

- 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 $\sim 10^5$ 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.



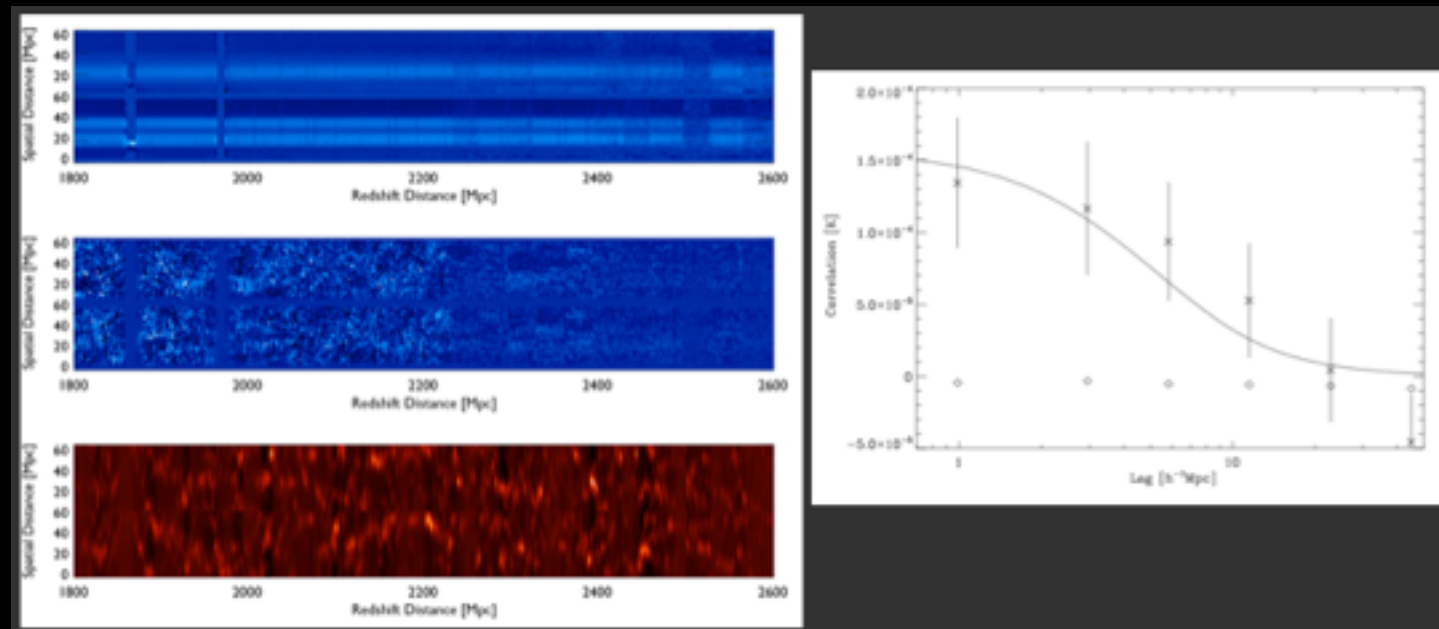
First intensity mapping
detection, Chang et al.

Intensity Mapping

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CHIME



First intensity mapping detection, Chang et al.

HIRAX

- We would like to measure dark energy via intensity mapping.
- Natural design: smallish dishes (6m) at $z \sim 1$ (~ 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 like to see...
- Natural des... effects. Too...
- BAO signal...
- Significant c... digital elect...
- HIRAX sup... Partnership



high, no DE

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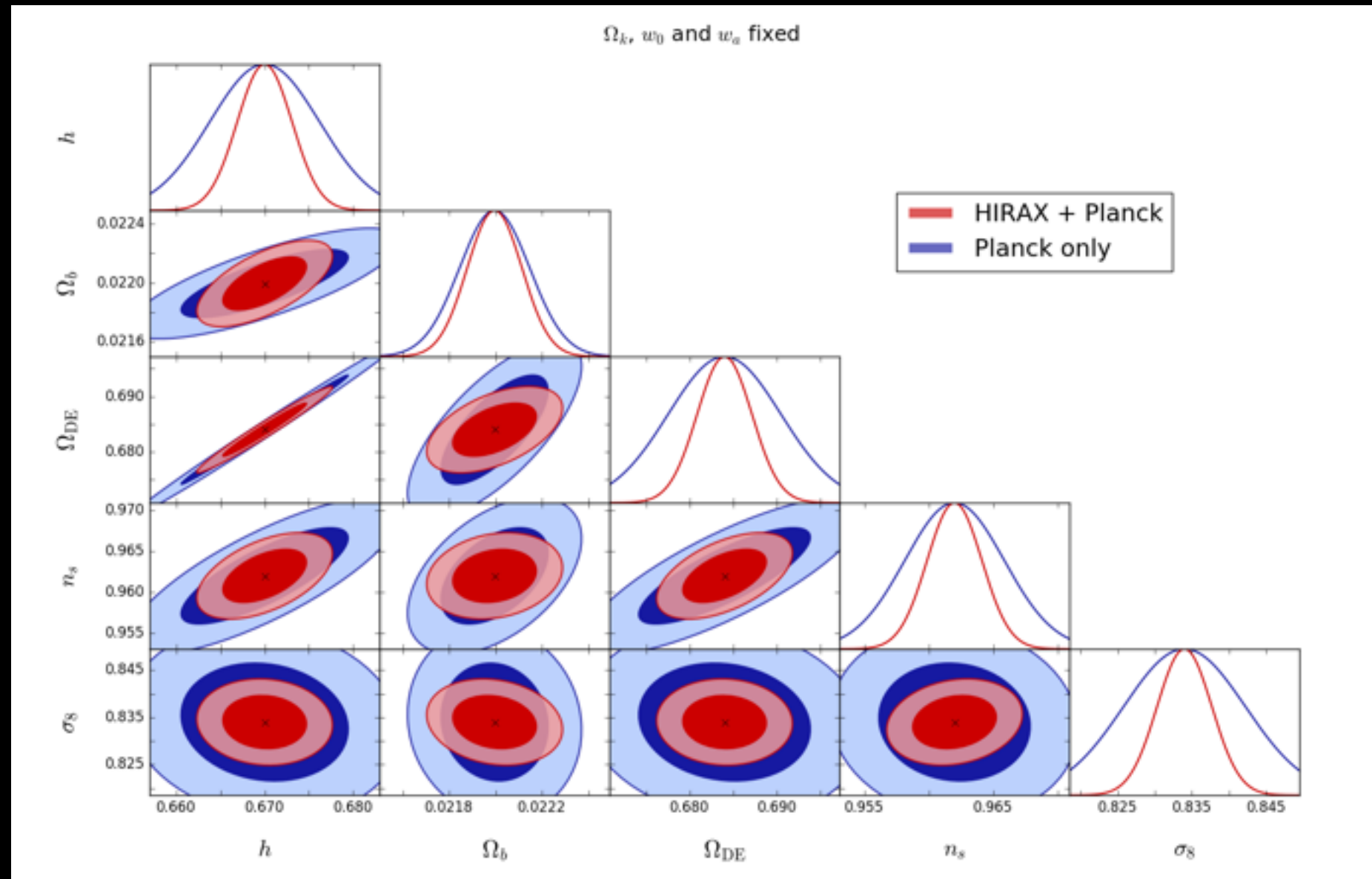


Current Design Plan

- 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...

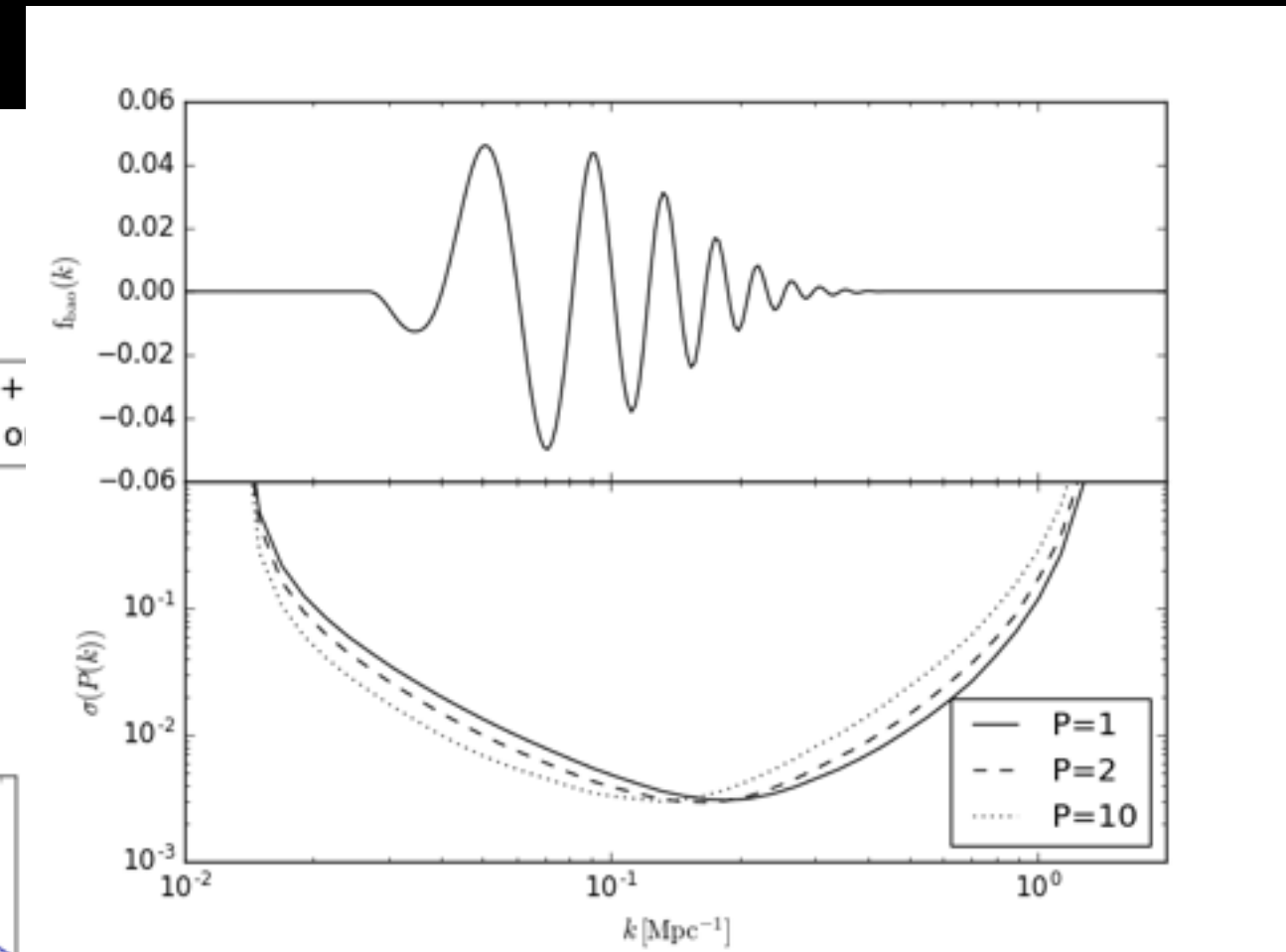
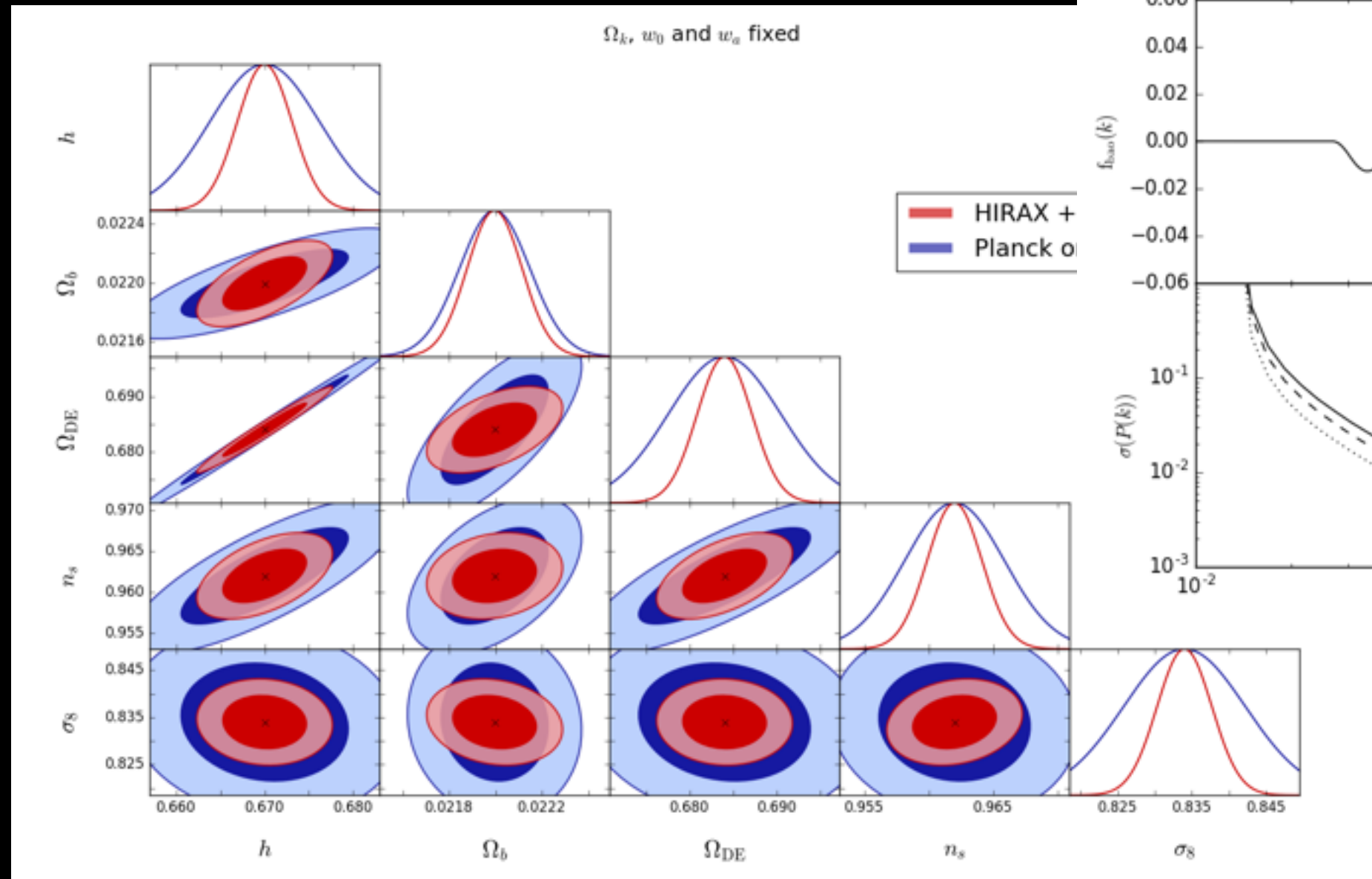


Forecasts (Amadeus Witzemann and Mario Santos)



1024 element for 4
years DE FOM ~300

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Few Months Ago



<2 weeks ago



Jacques & grad student Emily Kuhn installing new feed legs

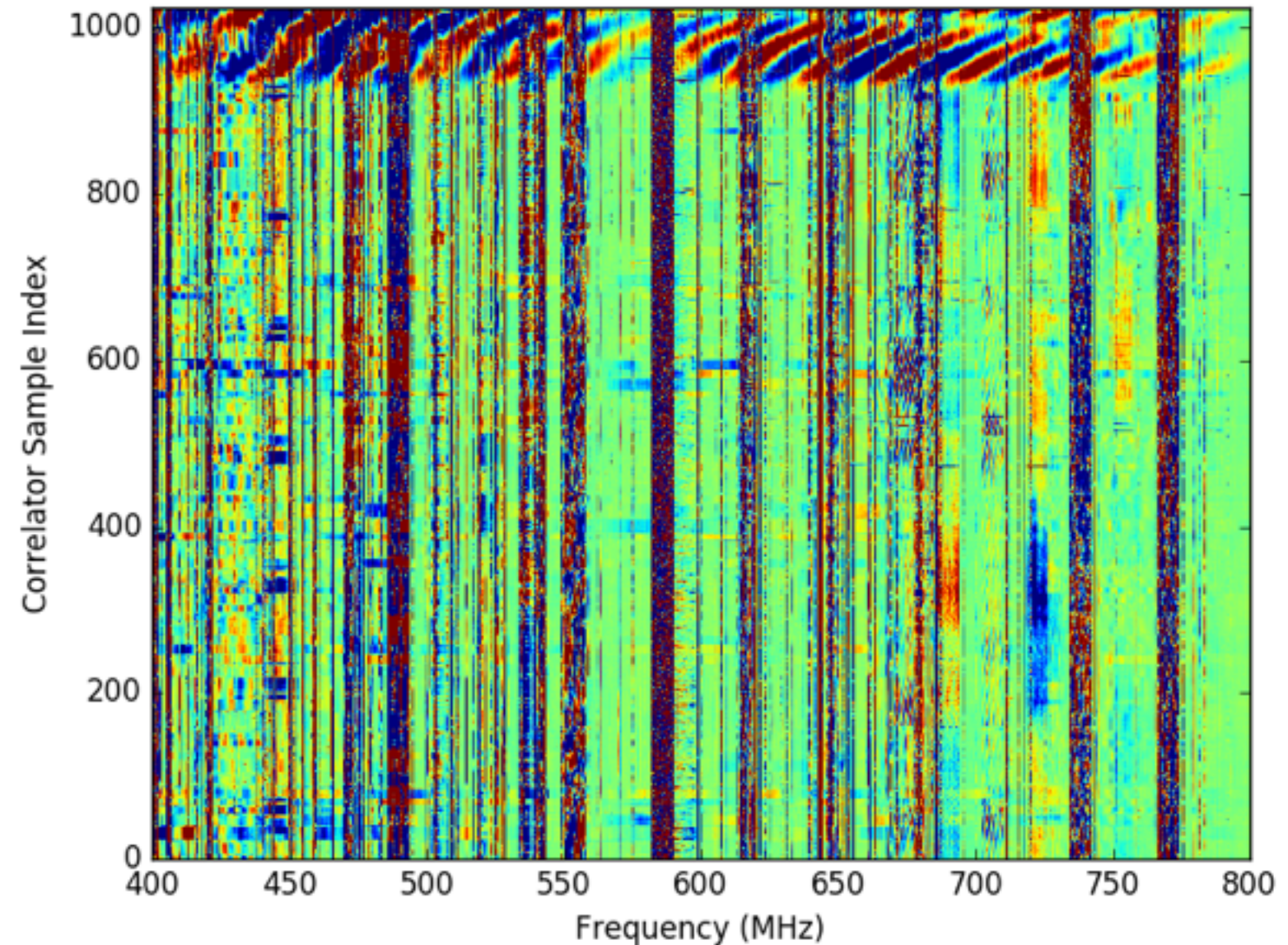
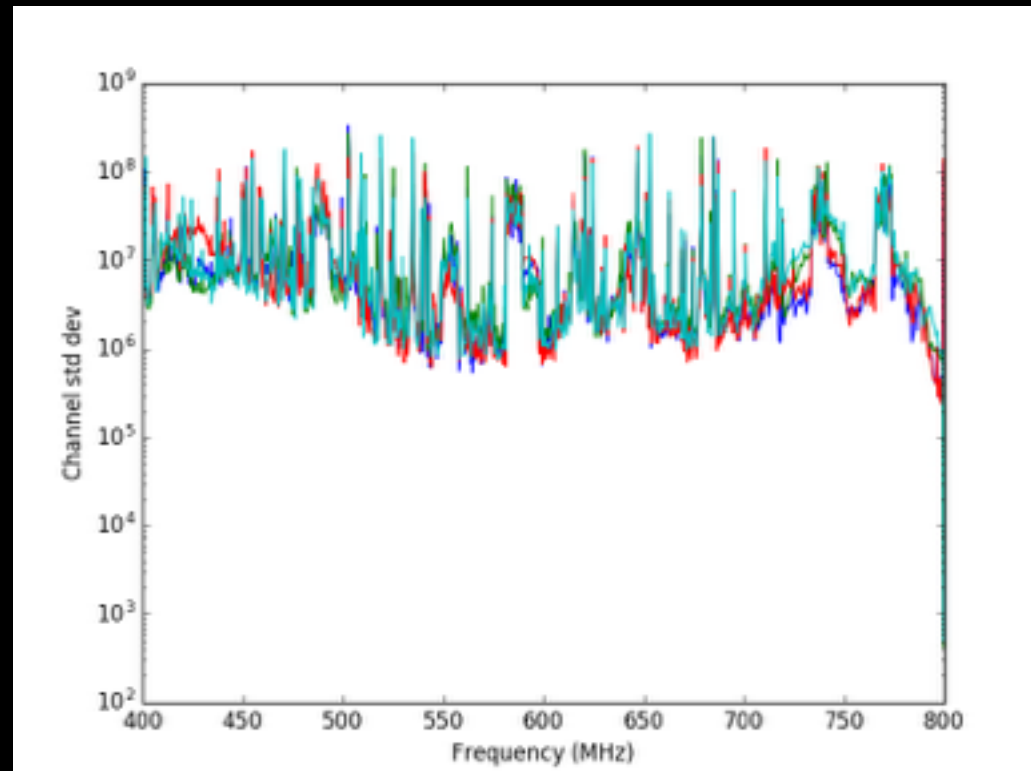
Current



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

Correlator Output (1 baseline) ~2 hours

Right: baseline with fringe
Bottom: noise as function
of frequency



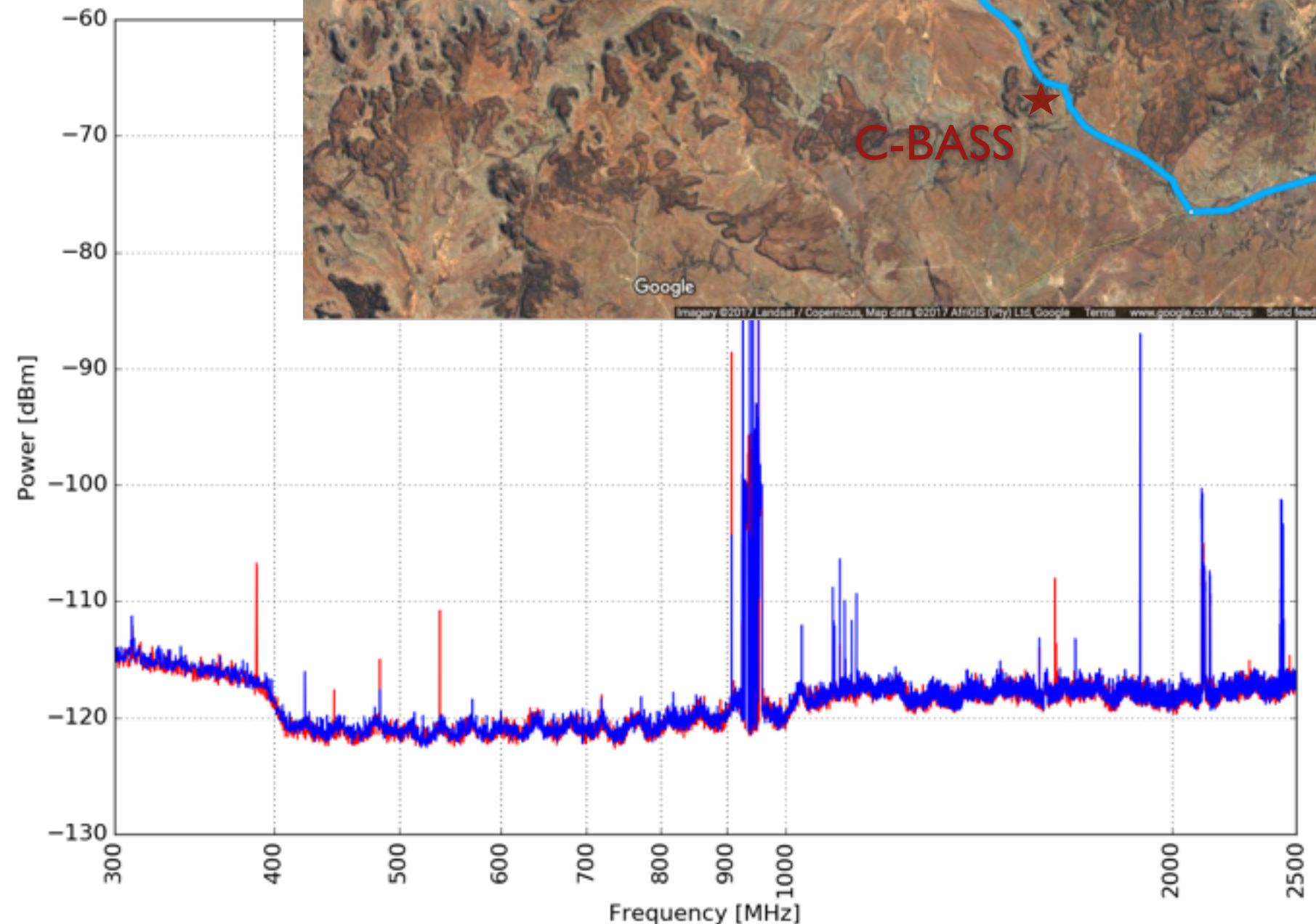
HartRAO Plan (slightly longer term)

- Finish/focus 8-element array, feeds arrive in August. Practice beam-forming/calibration etc.
- Currently appears we will be allowed in Karoo in ~18 months (statutory minimums for various rezonings etc.)
- In preparation, build out HartRAO install to ~32 dishes (enough space to fit them all).
- Plan to keep dishes running here for VLBI-type application, particularly FRB localization.

RFI @Klerefontein

Full array to be sited in Karoo between core site and SKA support site (Klerefontein).

UHF TV station in area has been turned off, RFI now looks fantastic.



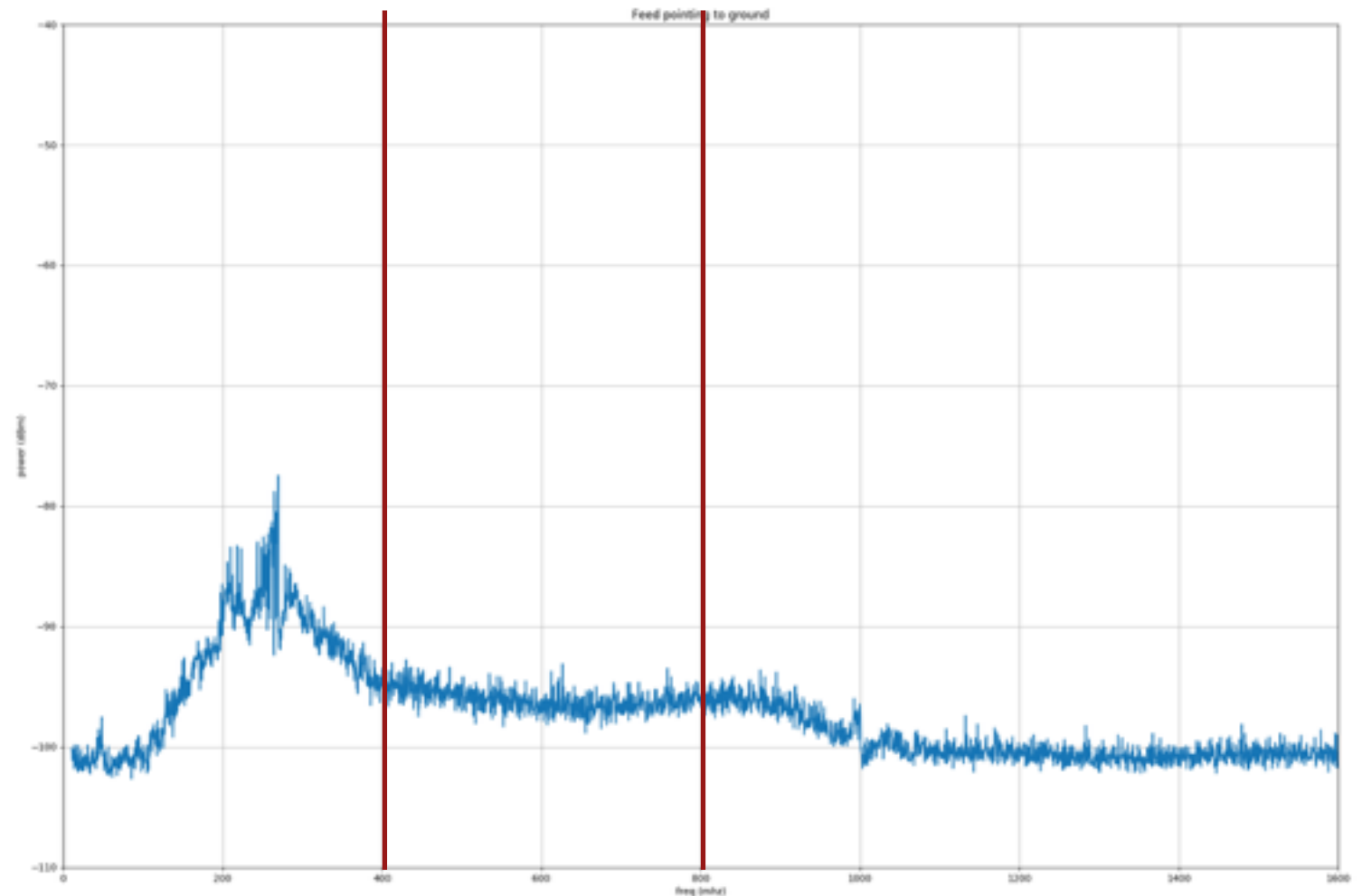
Site Test w/Feed

Real feeds have band response - want to know if e.g. cell phone might cause problems

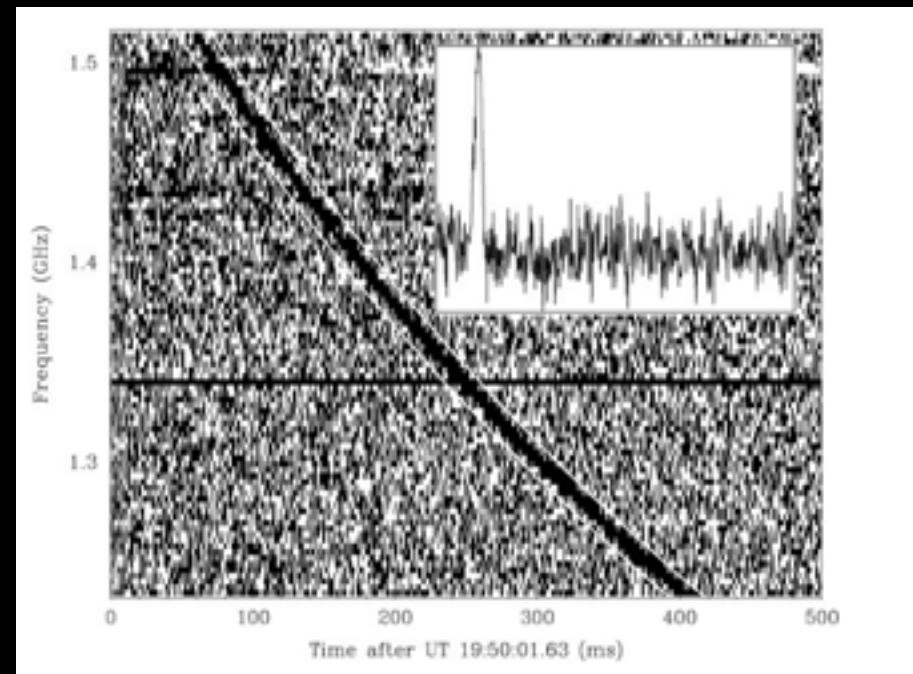


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Fast Radio Bursts



- What are they? We'd like to know...
- Where are they/how far away? We'd also like to know (repeater measured $z=0.19$)
- Can estimate mean optical depth as a function of redshift. Puts upper limits on FRB distances of $z=0.5-1$ or so.
- If τ cosmological, can get cosmology by measuring $\tau(z)$. In principle, few hundred FRBs can make good dark energy measurement (assuming neutral fraction known).
- Arrival time of different frequencies can give good tests of equivalence principle.
- FRBs possible way to get GW locations/redshifts (if FRBs come from things that put out GWs)

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

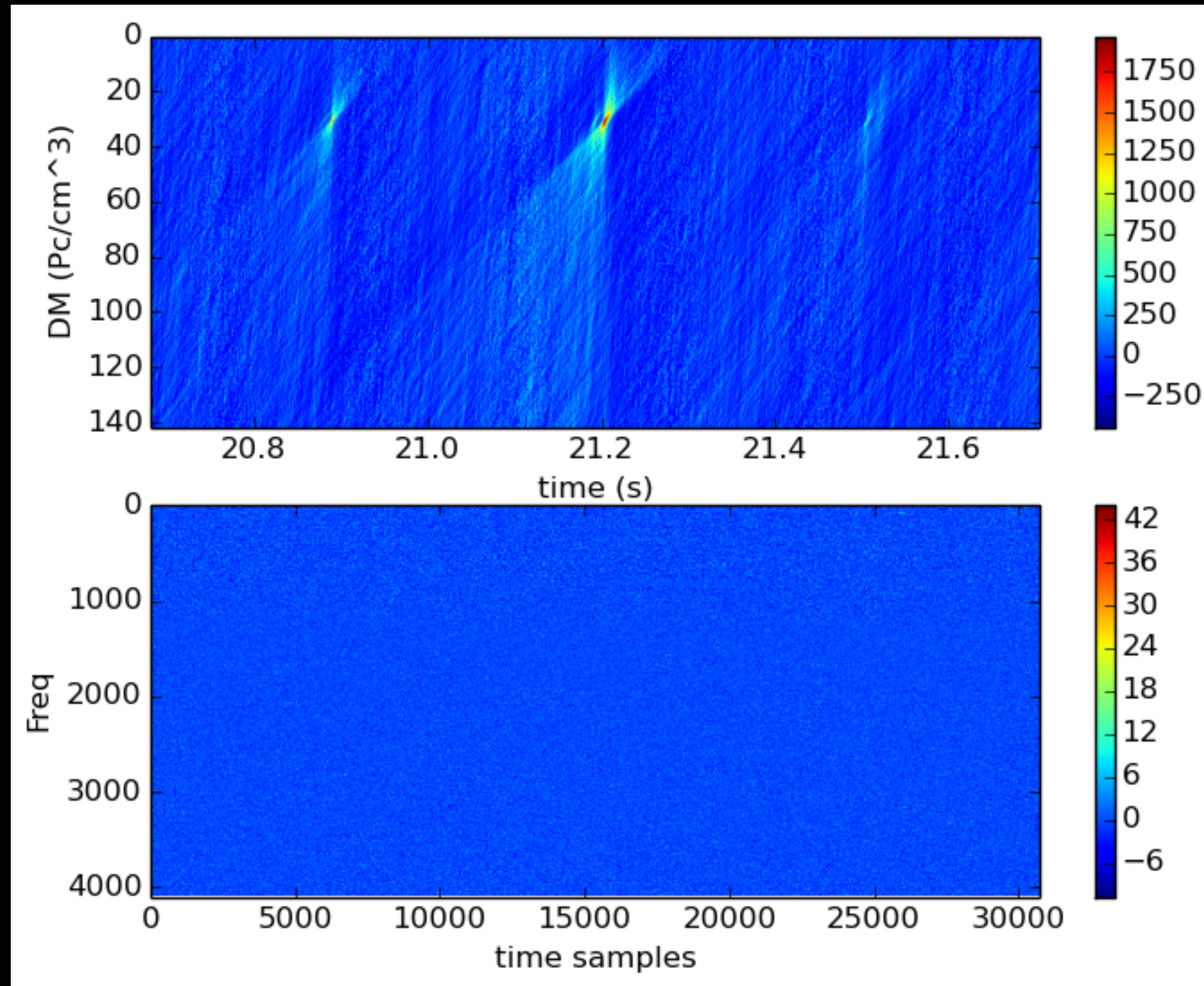
Scanning Across Known Pulsar

Arrival delay (s)=
 $4150 \cdot \text{DM} / \nu^2_{(\text{MHz})}$.

$\text{DM} = 500,000 \cdot \tau$

Transform takes
frequency-time to DM-
time, stacking power
from unknown DM in
 $n_{\text{time}} \cdot \log n_{\text{channel}}$
time.

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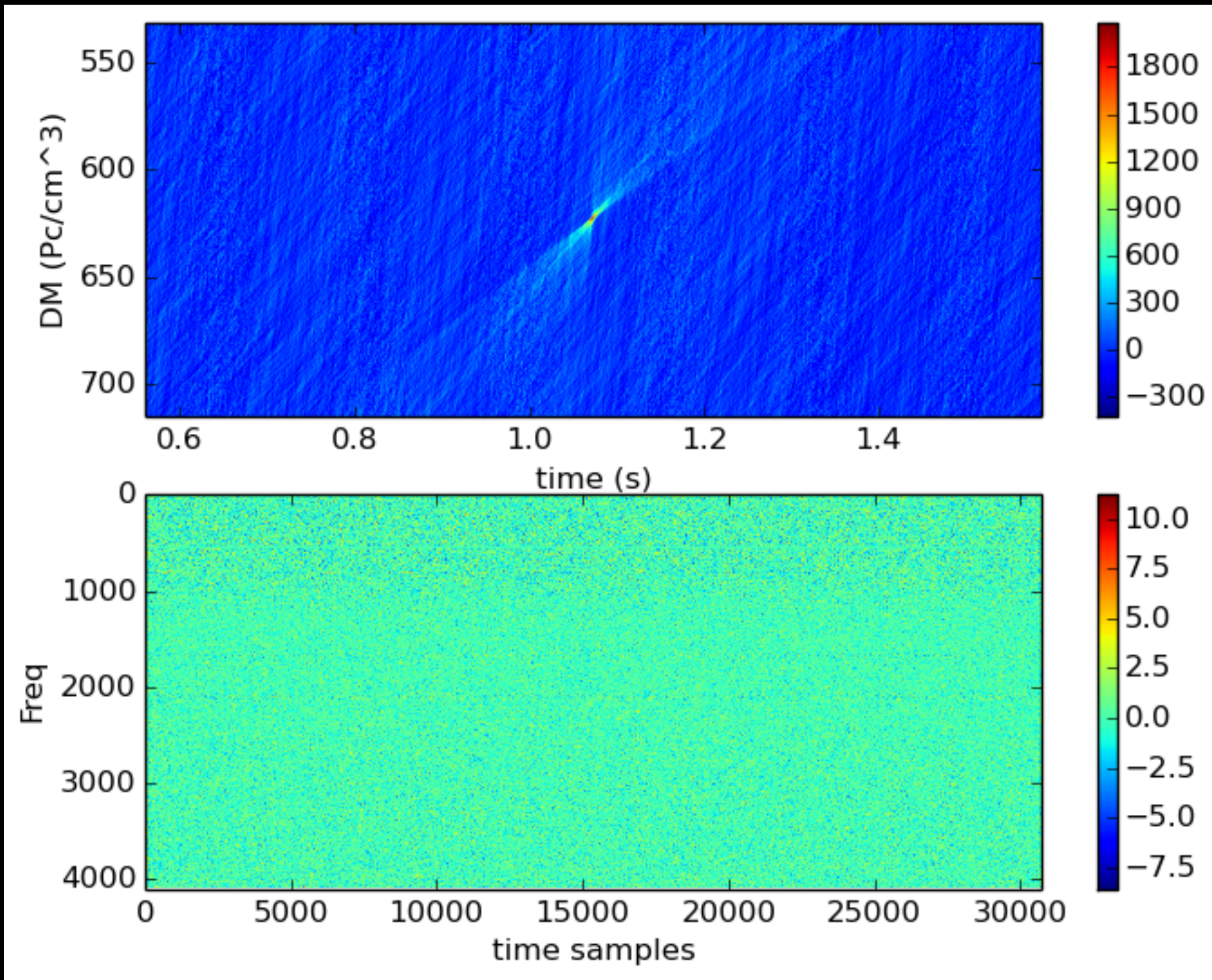


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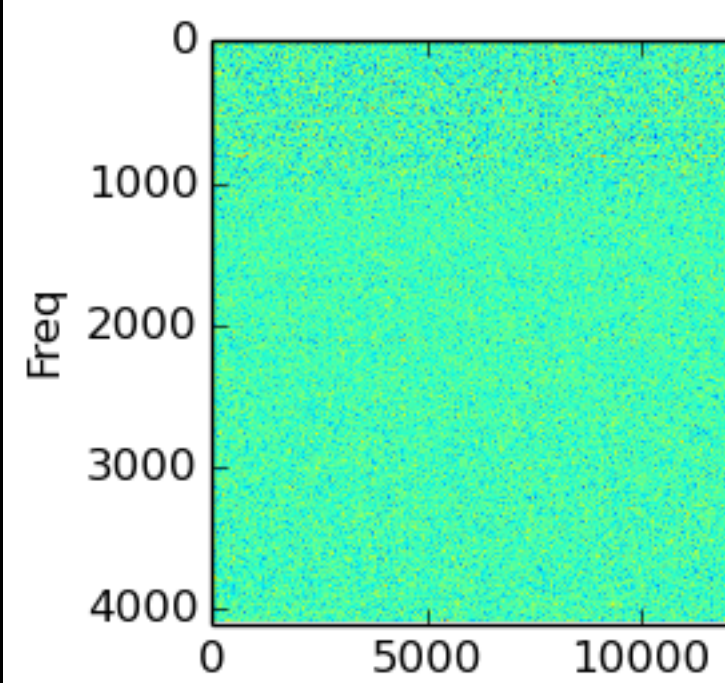
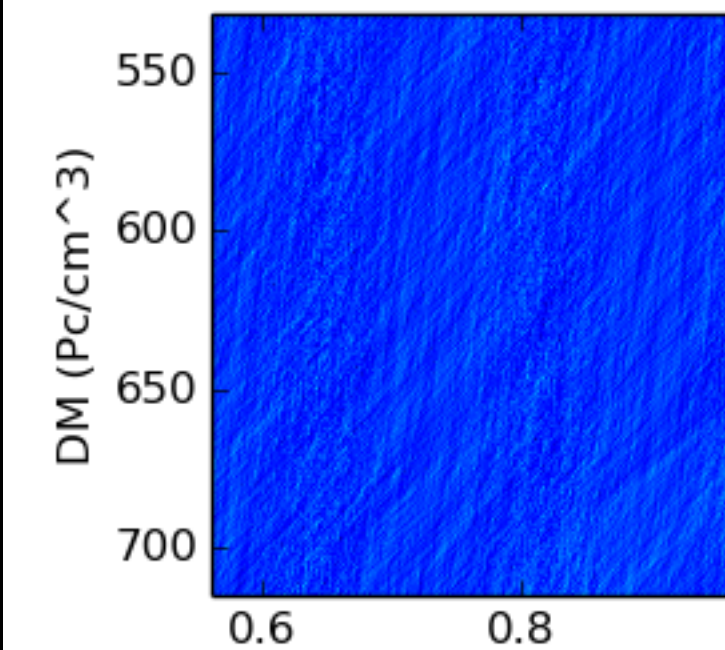
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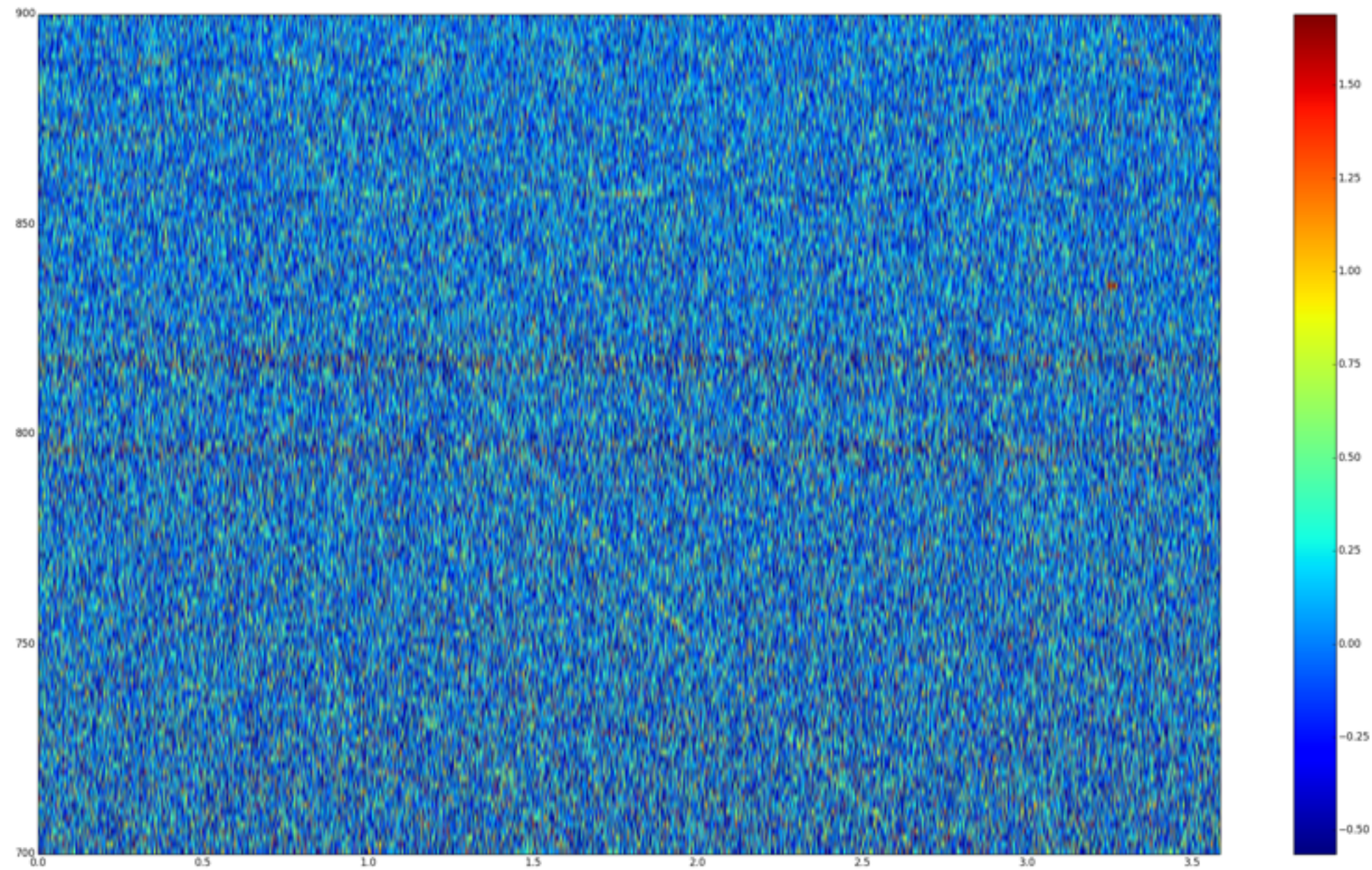
FRB w/ GBT



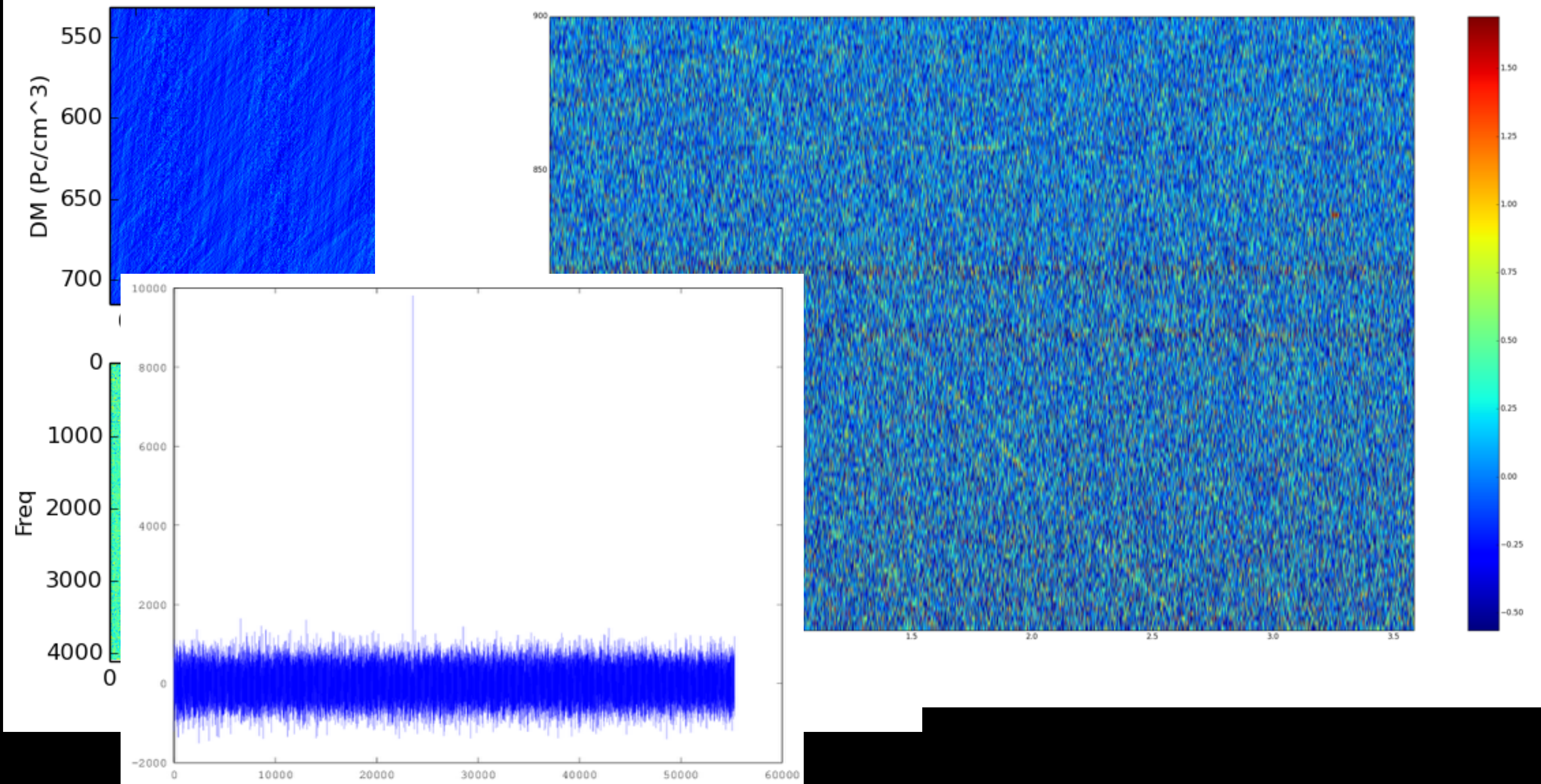
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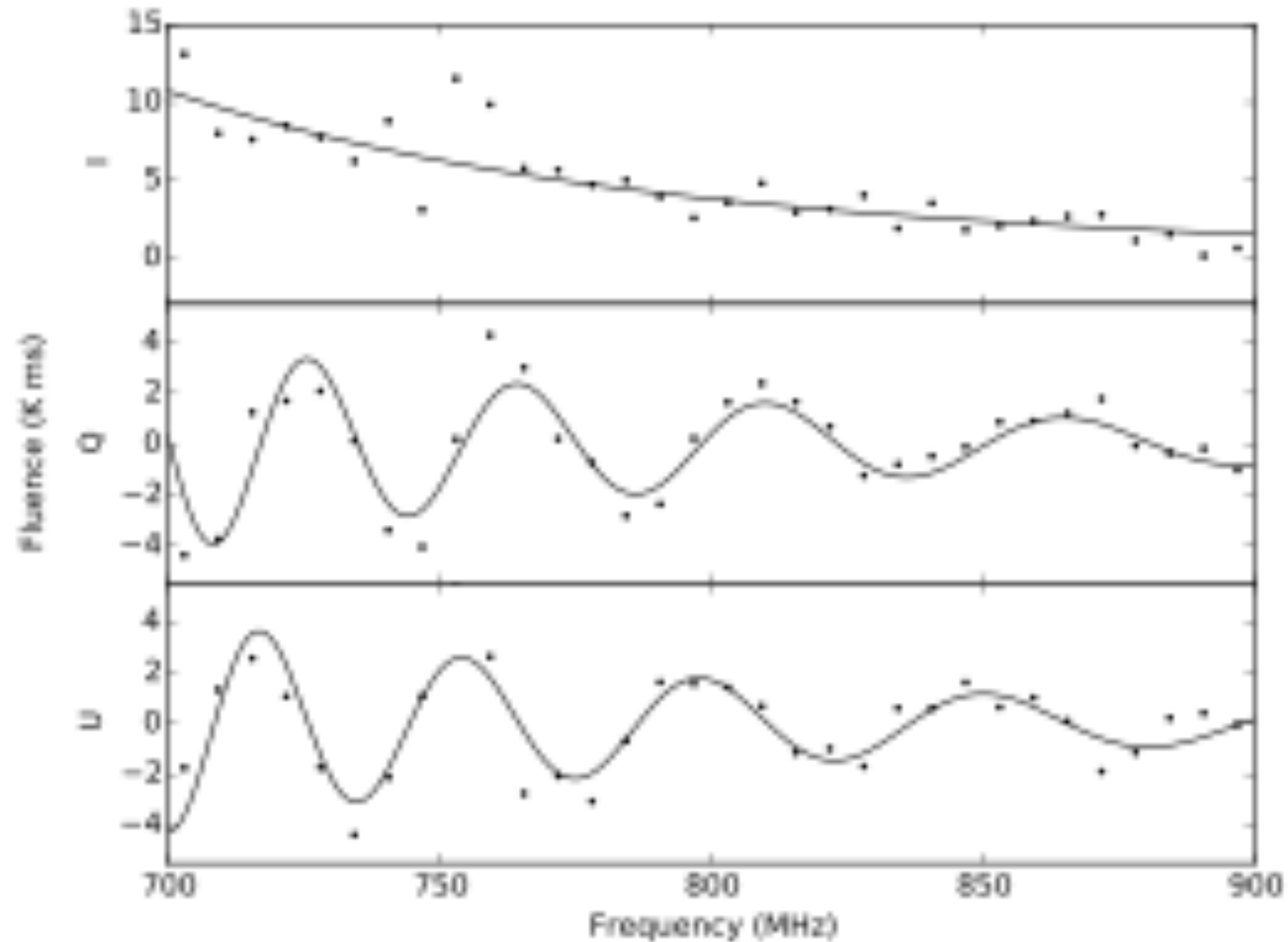
time samples



FRB w/ GBT



Faraday rotation detected



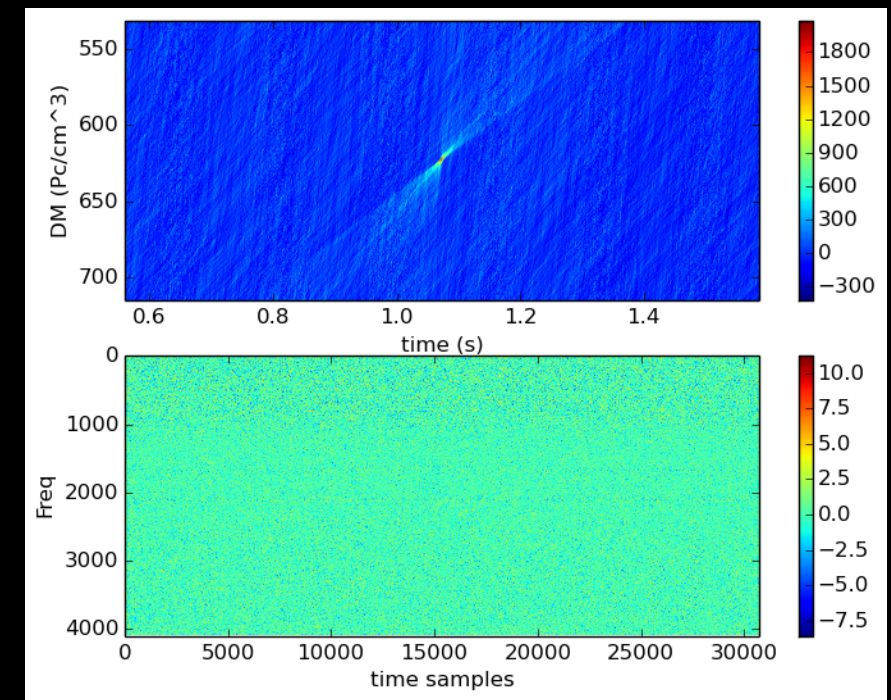
Magnetization is ten
times
As much as Milky
Way and IGM
Can explain

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 $n_e < 1.3 \times 10^7 \text{ cm}^{-3}$ (95%), minimum size of DM region 10 AU.
- But, given Faraday rotation, there must be something “close”

HIRAX & Fast Radio Bursts

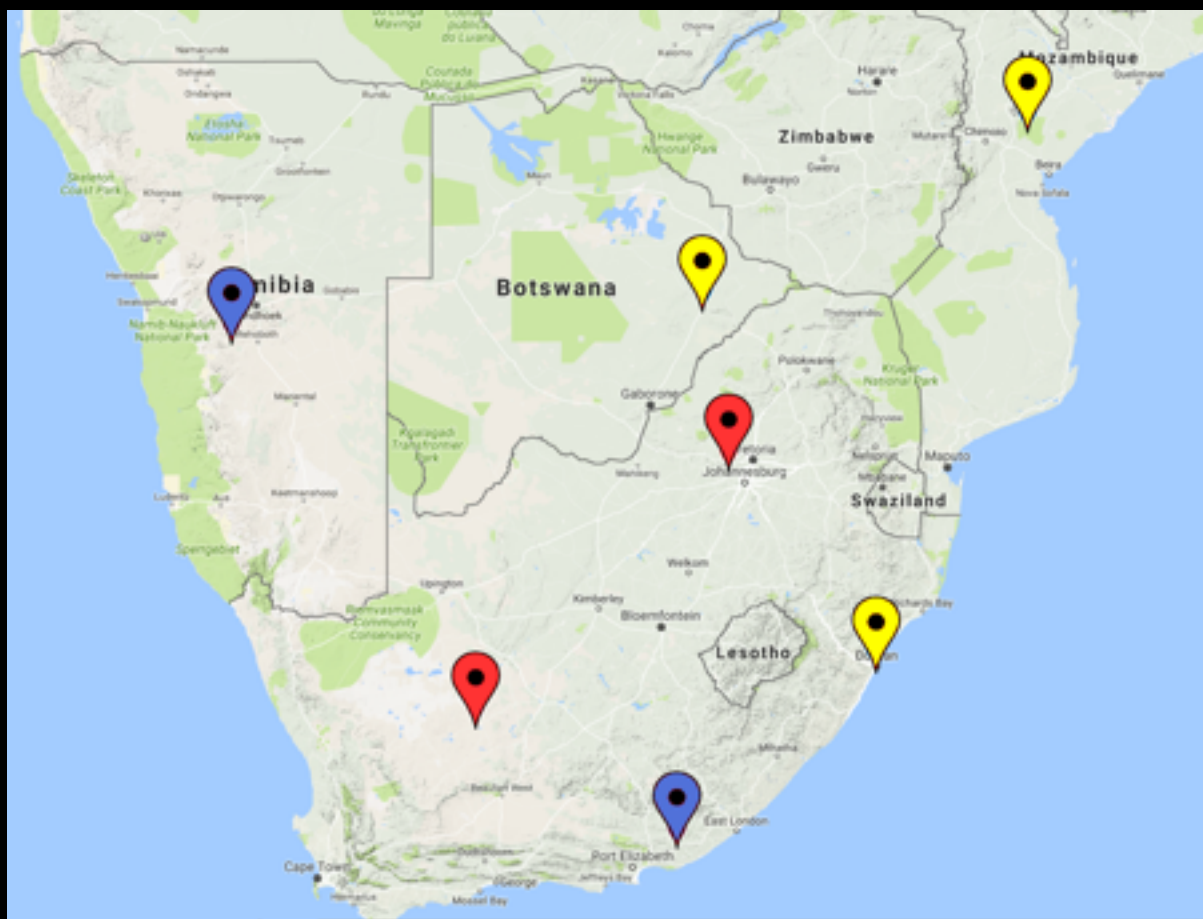
- At nominal sensitivity, get to $\sim 12 \mu\text{Jy}/\text{beam}/\text{day}$ (RMS).
- Fantastic FRB machine. For Euclidean counts, event rate proportional to dish diameter times # of beams, so should have $\sim 500\times$ Parkes rate/dozen(s?) per day.
- Search code developed for HIRAX tested on GBT, found first burst from GBT, first burst in HIRAX/CHIME band (which let us put it outside the galaxy), first with Faraday rotation...
- K. Smith has implemented same basic algorithm for CHIME FRB search.
- Search 10^3 beams 10^3 times/sec for 10^4 DMs over several possible lengths $\sim 2 \times 10^4$ #s/hour. Need at least 10σ , probably 15σ to be believable.



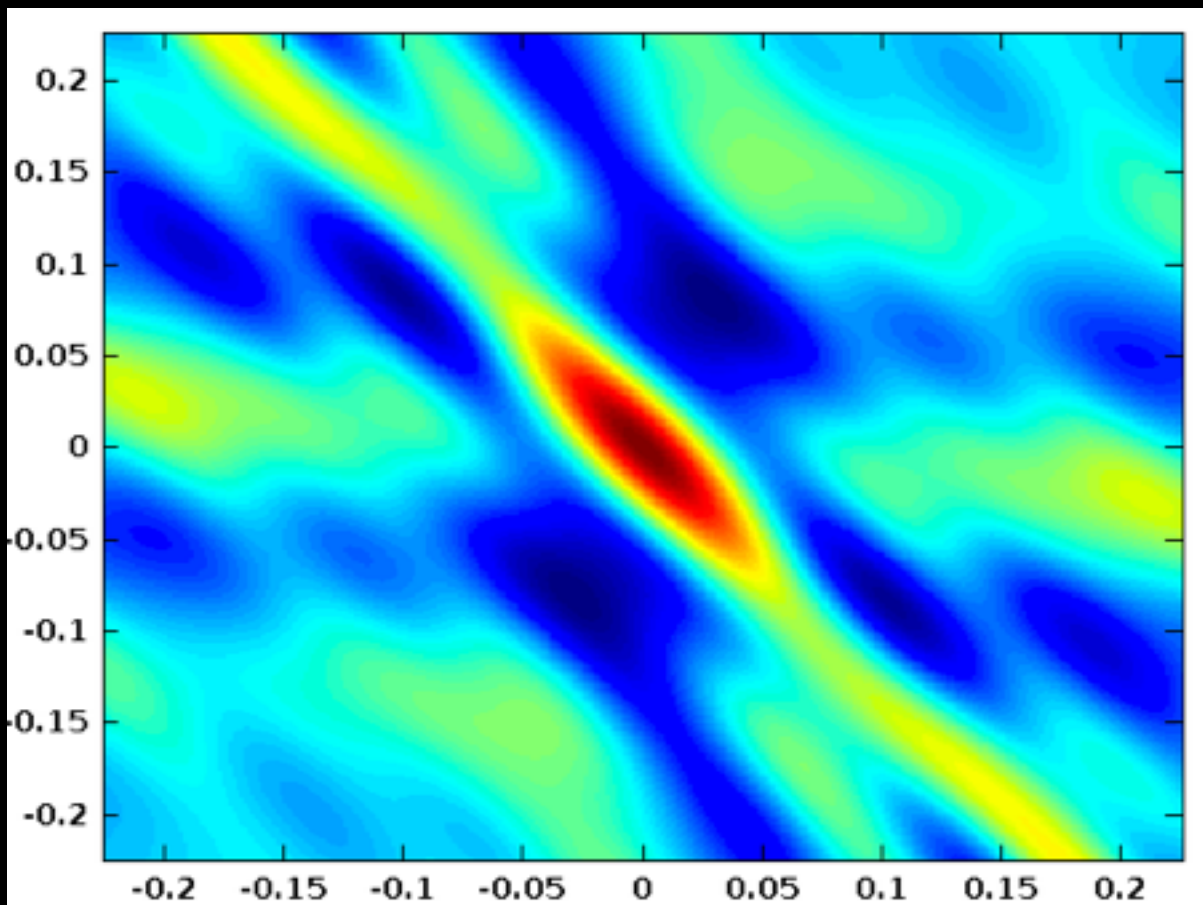
Outriggers

- 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 Network(?) 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.





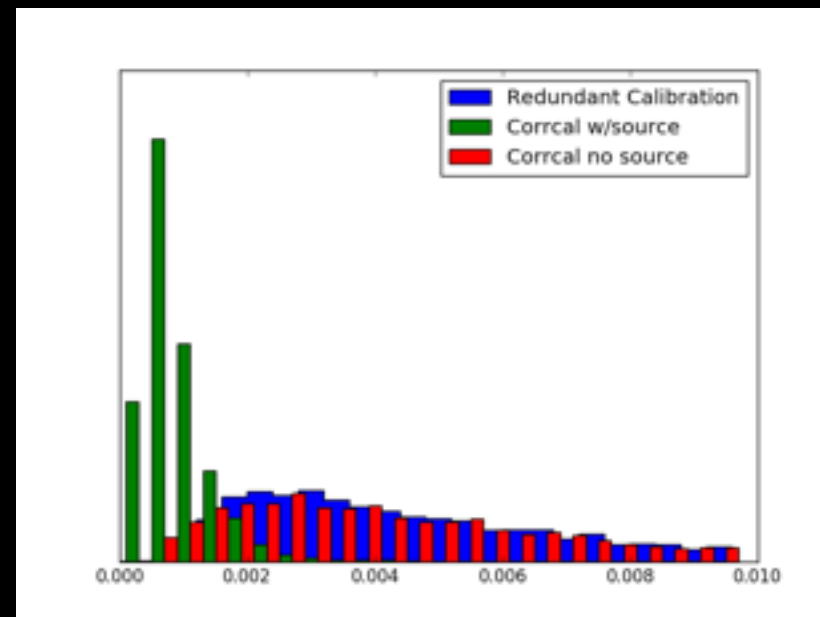
- ~1000 km baselines
- resolution ~100 mas, centroiding to few 10s of mas
- Red: funded/under construction. Yellow: proposed (Botswana, Durban)/advanced discussions (Mozambique). Blue: desirable



- Bottom: beam from red+yellow for flat-spectrum FRB. Plot axis in arcseconds.
- Matt McQ - “need 10^3 FRBs. w/redshifts.” We hope to provide this within a few years (plus gold sample outside of host galaxies?).

Redundant Calibration

- Milky way $\sim 1,000\times$ brighter than cosmological signal.
- Instrument must be understood/calibrated at 10^{-3}
- Calibration huge challenge - current methods assume redundant array.
- HIRAX extension for quasi-redundant arrays (JLS astro-ph/1701.01860) looks promising, being investigated by CHIME, PAPER/HERA as well.



HIRAX Status/Timeline

- Funded for >128 dishes (close to 256) from UKZN & NRF.
- SRE submitted to NRF, MRI to NSF (P.Timbie as PI). Outrigger proposal submitted for funding via SA/Canada/Africa trilateral research chair call.
- 8 dish prototype partially running (fully next month), dishes/back-end fully installed.
- Start more dishes at HartRAO ~end of year(?).
- Start installing 128 on-site when rezoning/EIA completed
- Start on 512 end 2019, and 1024 end 2020, subject to funding.

Summary

- Evolution of fluctuations set in the early universe sets large-scale properties of universe.
- CMB gives us snapshot of universe at 400,000 years when modes linear. CMB focus switching to polarization to search for inflation and measure neutrino mass.
- When fluctuations go nonlinear and form first stars*, signal imprinted on mean sky by 21 cm hydrogen line. We are searching for this from one of most remote locations on Earth; interference appears negligible.
- Dark energy drives angular size of fluctuations in recent universe. HIRAX (and CHIME, plus others) will measure dark energy via intensity mapping.
- We plan to build outriggers for fast radio burst localization with HIRAX. Would takes us from one localization total to many per day.