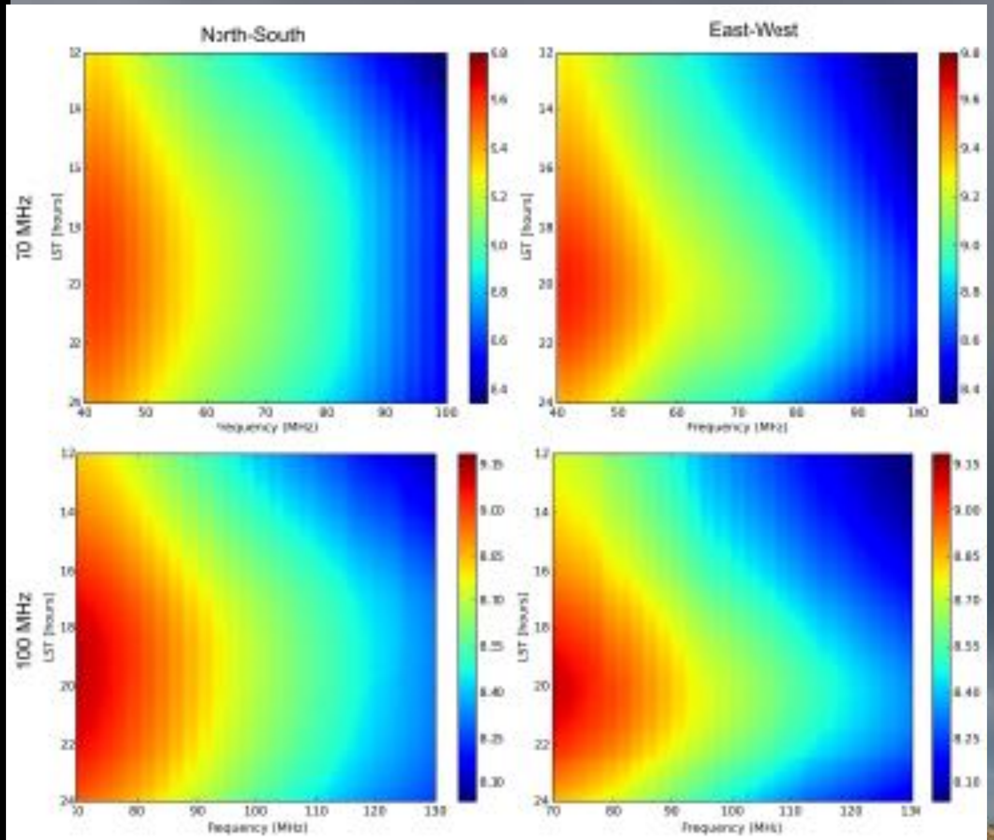
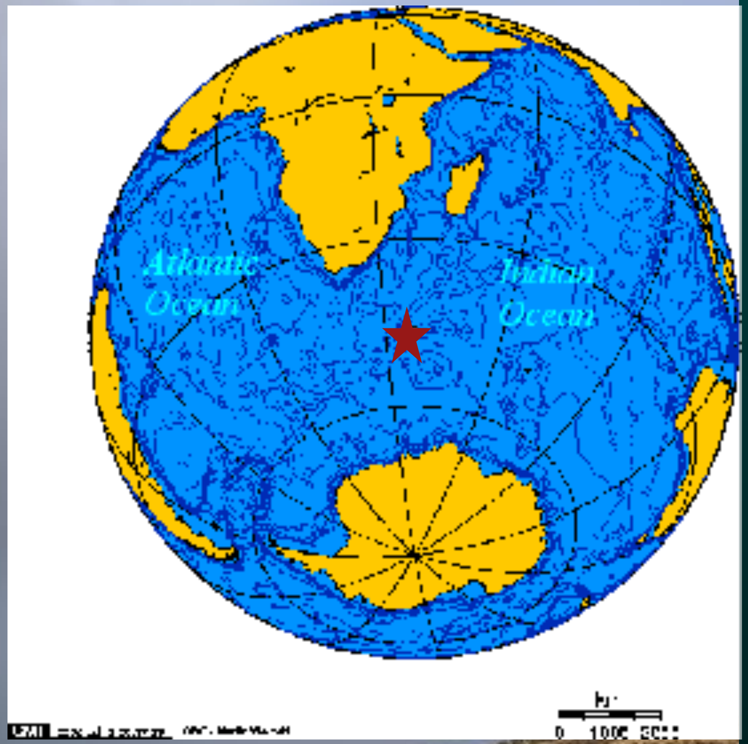
HIRAX and Fast Radio Bursts

Jonathan Sievers (McGill/UKZN) for the HIRAX Collaboration

Not Going to Talk About…

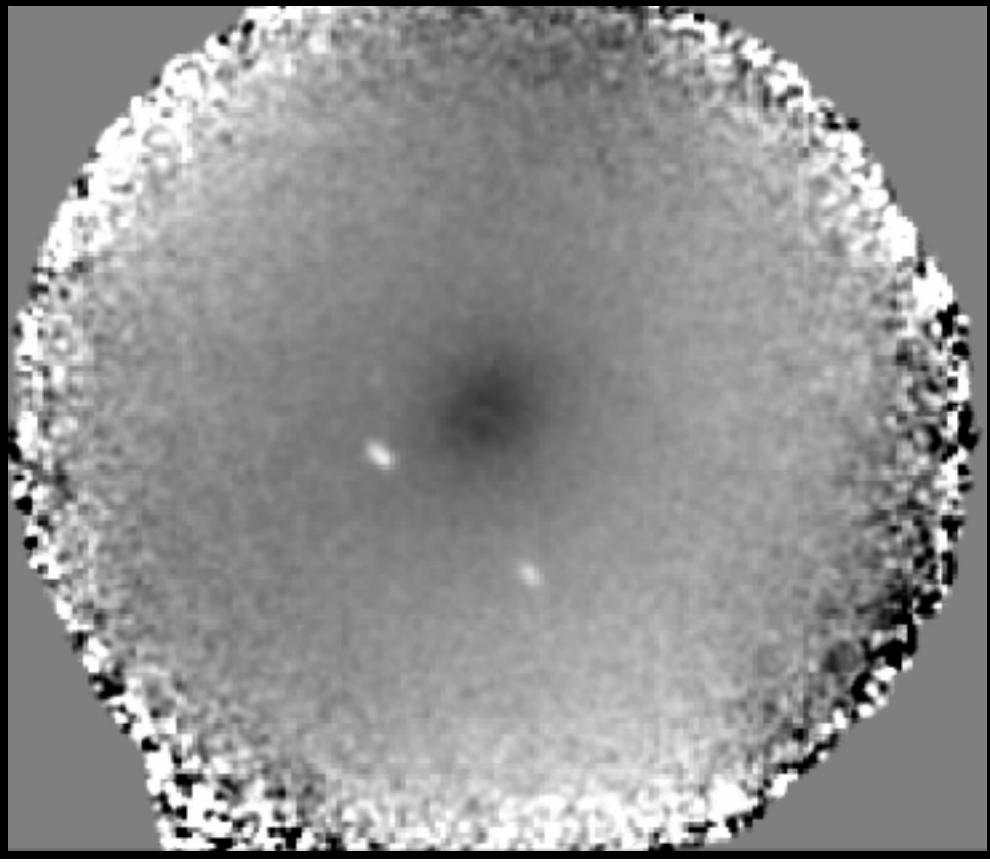
(PRI^{Z}M on Marion Island)

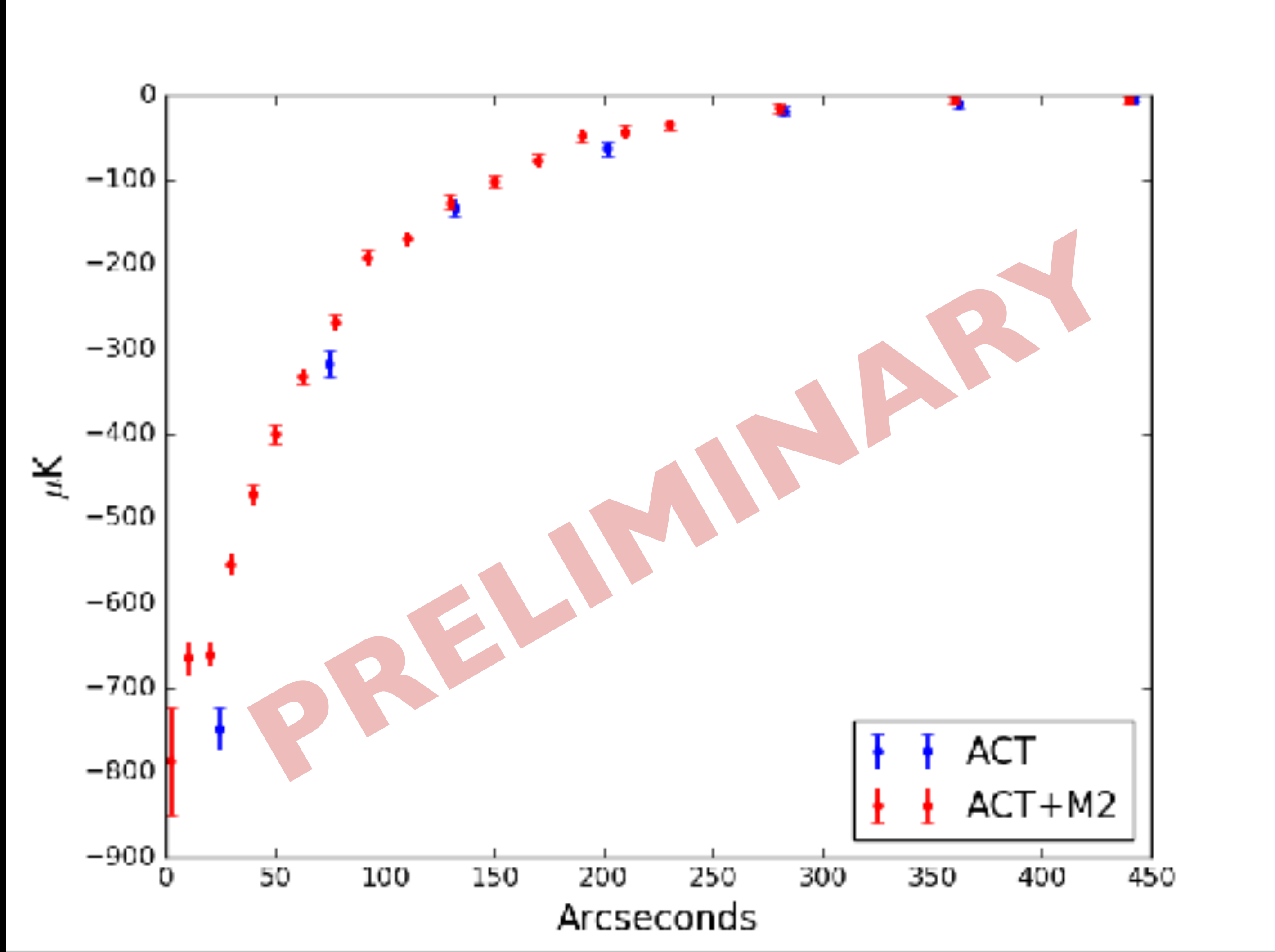




Also Not Going to Talk About…

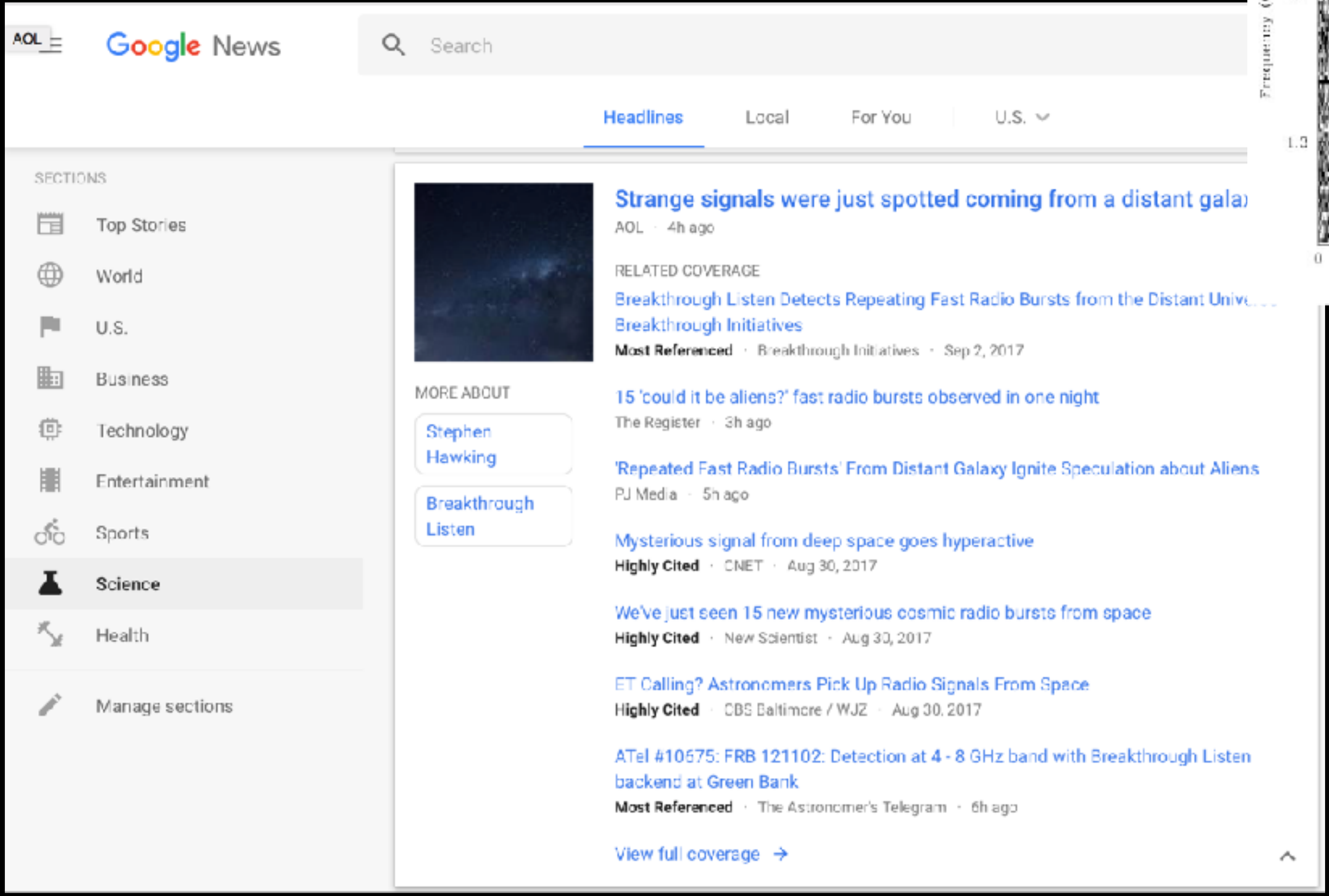
- Mustang 2 Camera on Green Bank Telescope maps clusters in SZ effect
- 9" resolution allows views of cluster impossibile for ACT/SPT/ Planck
- 100m telescope means lots of sensitivity.
- Example -11 hour Zw3146 observation, ACT-only and ACT+M2 joint analysis in projected cluster SZ profile.
- Analysis not complete, but more coming…

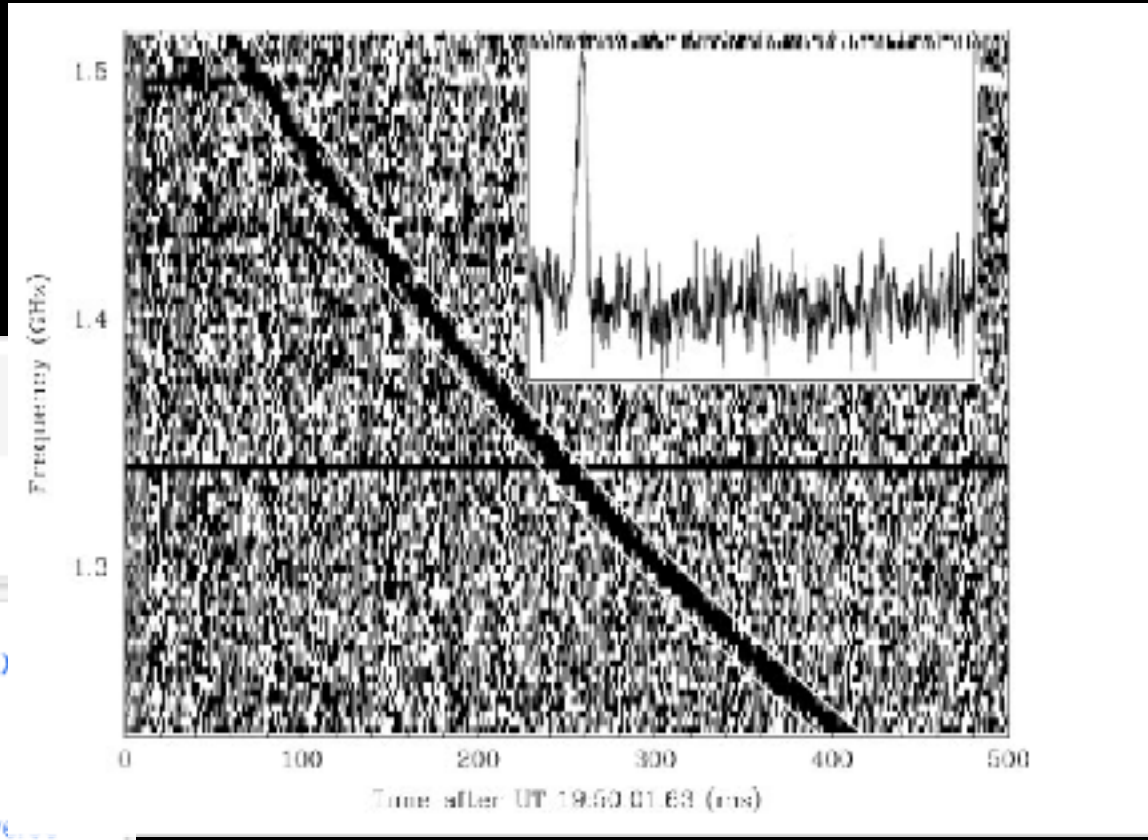




Top: M2 map of ZW3146 (10' full map size)
Bottom: ACT-only and ACT+M2 SZ profile

Fast Radio Bursts

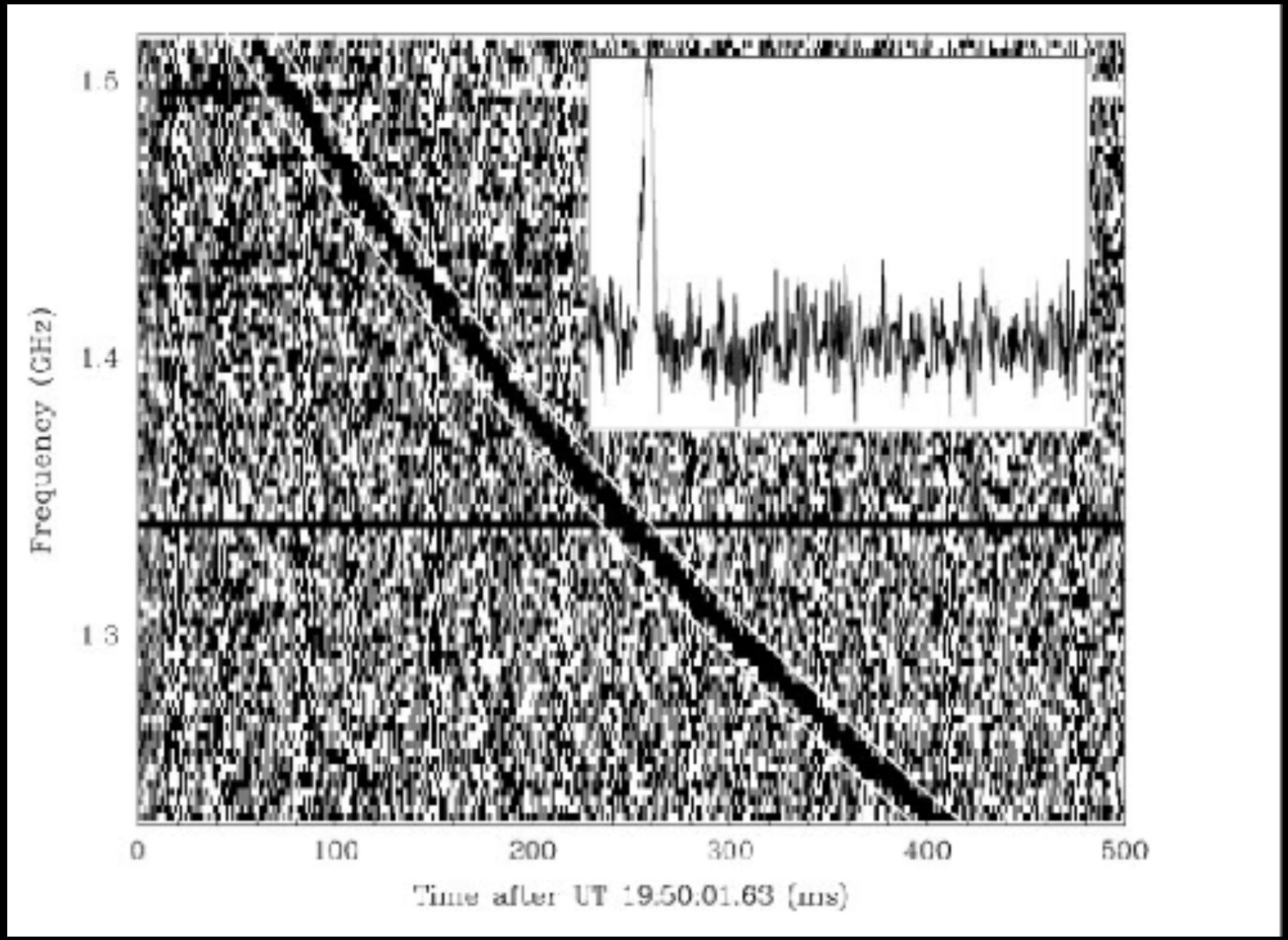




FRBs are mysterious bursts discovered a decade ago, and remain unexplained.

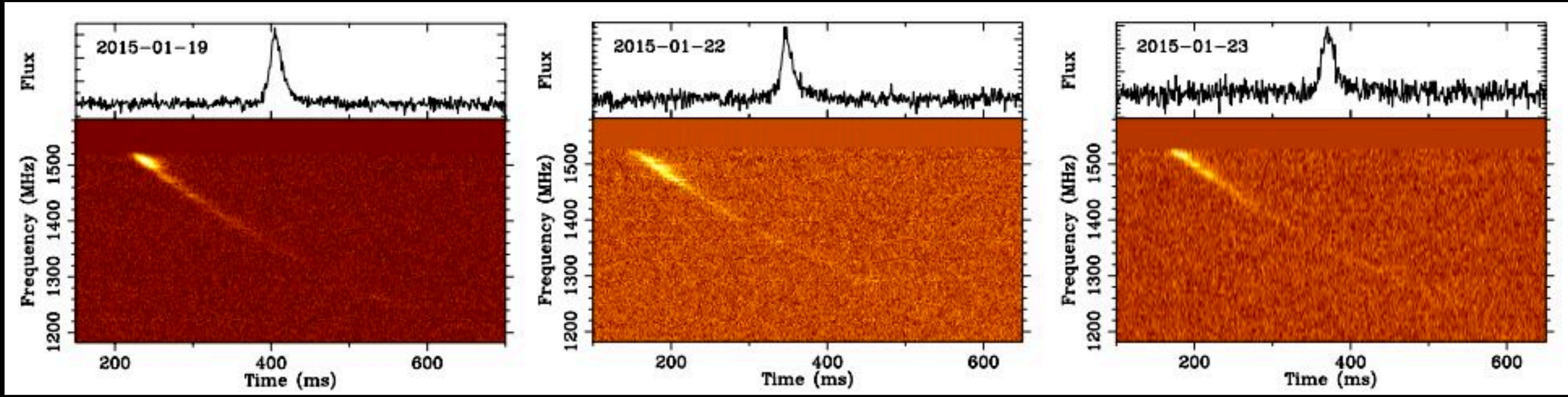
HIRAX will be premiere instrument.

Dispersion
(or why were FRBs unnoticed)



- 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/488,000

FRBs Were Long Doubted



- For many years, Parkes was the only telescope to see FRBs.
- The above look like FRBs, right?
- No! Delay is not exactly λ^2, and they show up in multiple beams. Means telescope not in focus -> near field event.
- This class (perytons) was also more common around noon on weekdays, and when telescope was pointed in a certain direction.

In 2015, tracked down to opening Parkes microwave oven while running

A Brief History

- First burst reported by Lorimer in 2007
- A handful more from Parkes over the next several years.
- Arecibo reports a burst very close to the galactic plane in 2014 (receiver from same lab as Parkes)
- Late 2014, circularly polarized (20%) FRB found at Parkes. Quick followup fails to find multiwavelength counterpart.
- 2015 - GBT discovers an FRB (in HIRAX pipeline test!), first with linear polarization, enables Faraday rotation measure. At 800 MHz, first seen out of L-band
- 2015/16 - FRB 150418 thought to have counterpart, many interesting papers written. Turned out to be variable AGN
- 2016 - Arecibo burst seen to repeat. UTMOST begins discovering. ~20 total known now
- 2018 - CHIME turns on, quickly announces FRBs. ASKAP announces ~20 new events.
- 2019 - CHIME dumps another 13, including only second known repeater.
- Total of 65 now reported at frbcat.org.

What we (Don't) Know

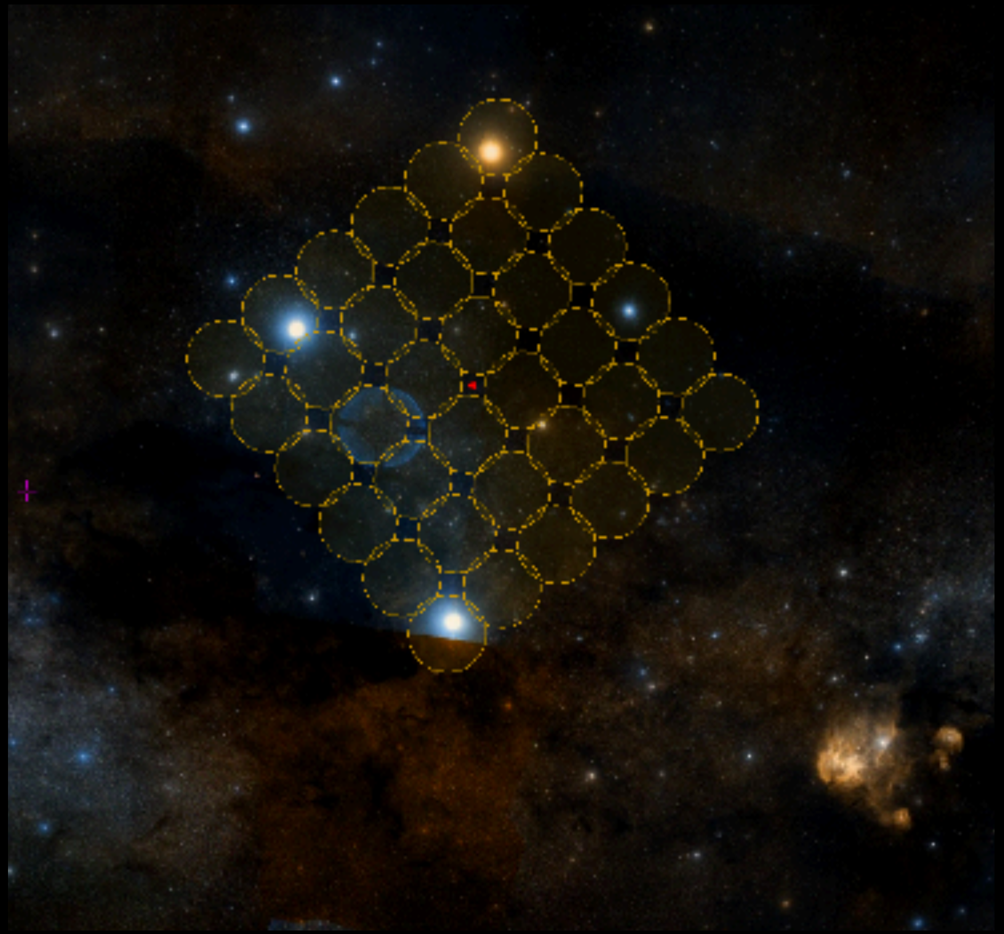
- Two FRBs have been seen to repeat. Do the others? How many classes are there?
- At least some part of DM can (must) come from close to the FRB
- Polarization properties all over the map - some circularly, some linear (up to 80%), some not.
- Rotation measures all over the map - 0-186 for non-repeating, $>10^5$ for repeater.
- Spectral behavior all over the map - some from propagation effects.
- Not known if counts are Euclidean.
- Durations all over the map µsecs to msecs.

Why Aren't There More?

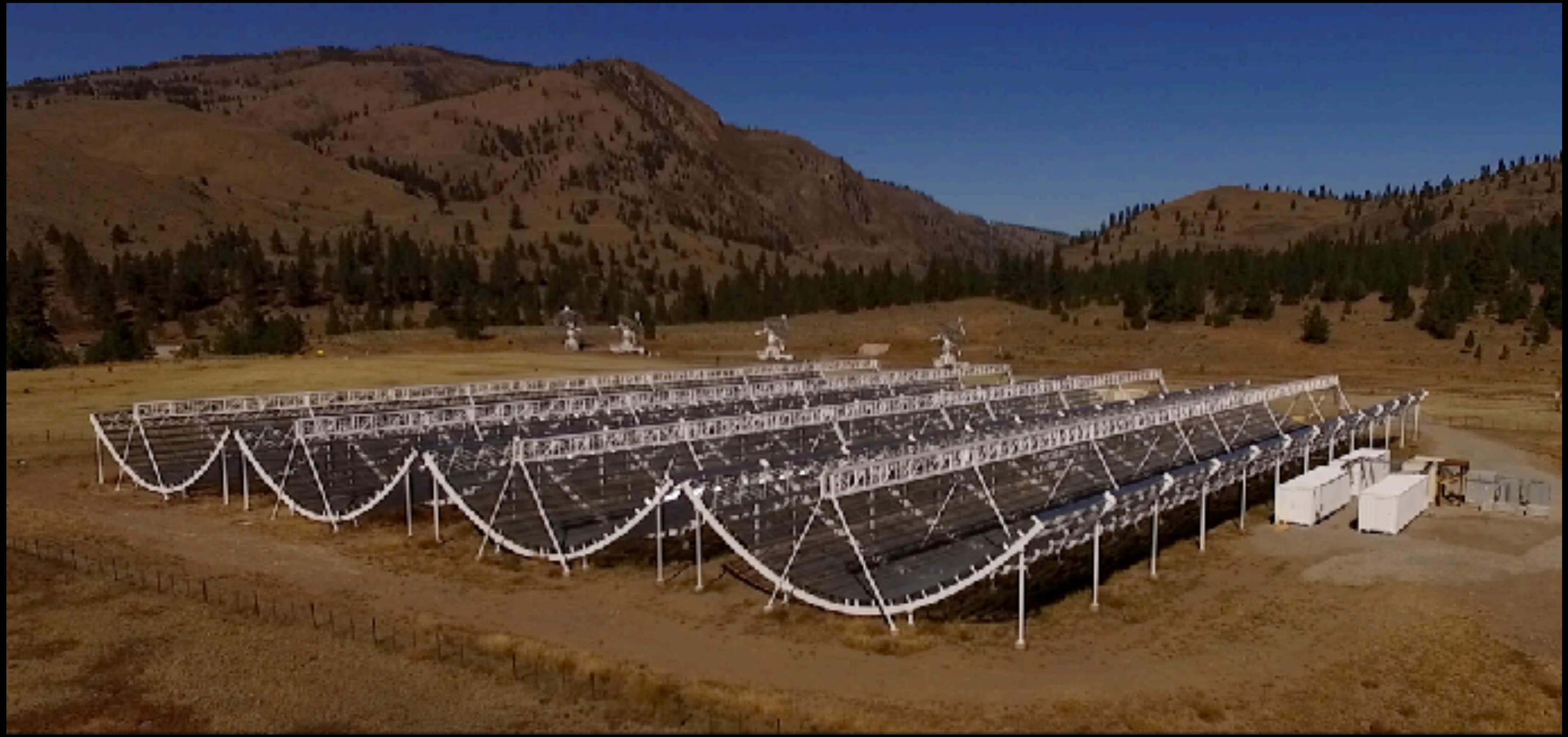
- Inferred event rate at Parkes sensitivity is several thousand per sky per day.
- For Euclidean counts, and everything else equal, event rate scales like # of beams times dish diameter.
- 13 beams at 21cm at Parkes (64m diameter) - f_{sky}~1.3e-5.
- So, 1 in 70,000 happens to flash where Parkes is pointing - 1 event every couple weeks means thousands per sky per day.
- To improve: more collecting area, and (much!) more sky coverage.

ASKAP

- Australian SKA Pathfinder has 36 beams per 12m telescope -> each telescope is 36*12/13*64=half Parkes.
- 36 ASKAP telescopes operating independently ("fly's eye mode") gives ~20x Parkes rate.
- Despite turning on in 2017, ASKAP has already found as many FRBs as Parkes.
- Spread out nature of ASKAP means computationally challenging to combine dishes together efficiently.



CHIME



- Canadan Hydrogen Intensity Mapping Experiment is 4 100x20m cylinders with 256 feeds, operating at 400-800 MHz.
- Sees whole northern sky every day, instantaneous FOV is hundreds of times Parks, with 2.5x collecting area.
- Uncertain spectral behavior makes extrapolation from 1.4 GHz hard, but should be ~100x Parkes rate, or several per day (large errors).
- (I) expect reporting rate to shoot up as telescope gets calibrated.

Location, Location, Location

- We’ve now found several dozen, why don’t we know anything?
- Repeater localized to z~0.2 dwarf galaxy, near a VLBI radio source.
- FRBs *found* with low-res telescopes, so no counterparts.
- So, we have no redshifts, no host galaxies, for “typical” FRBs. Makes progress hard.

HIRAX

- We would like to measure dark energy via intensity mapping.
- Natural design: smallish dishes (few m) 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

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

NRF National Research Foundation
SARAO South African Radio Astronomy Observatory

DUT DURBAN UNIVERSITY OF TECHNOLOGY

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McGill

UNIVERSITY OF OXFORD

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PERIMETER INSTITUTE

UNIVERSITY OF TORONTO

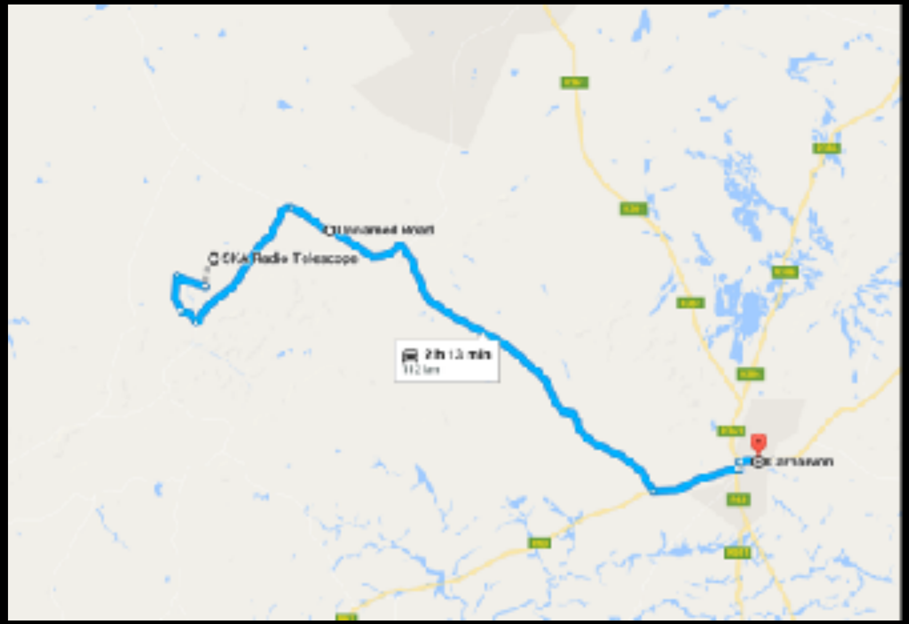
THE UNIVERSITY of WISCONSIN MADISON

Yale

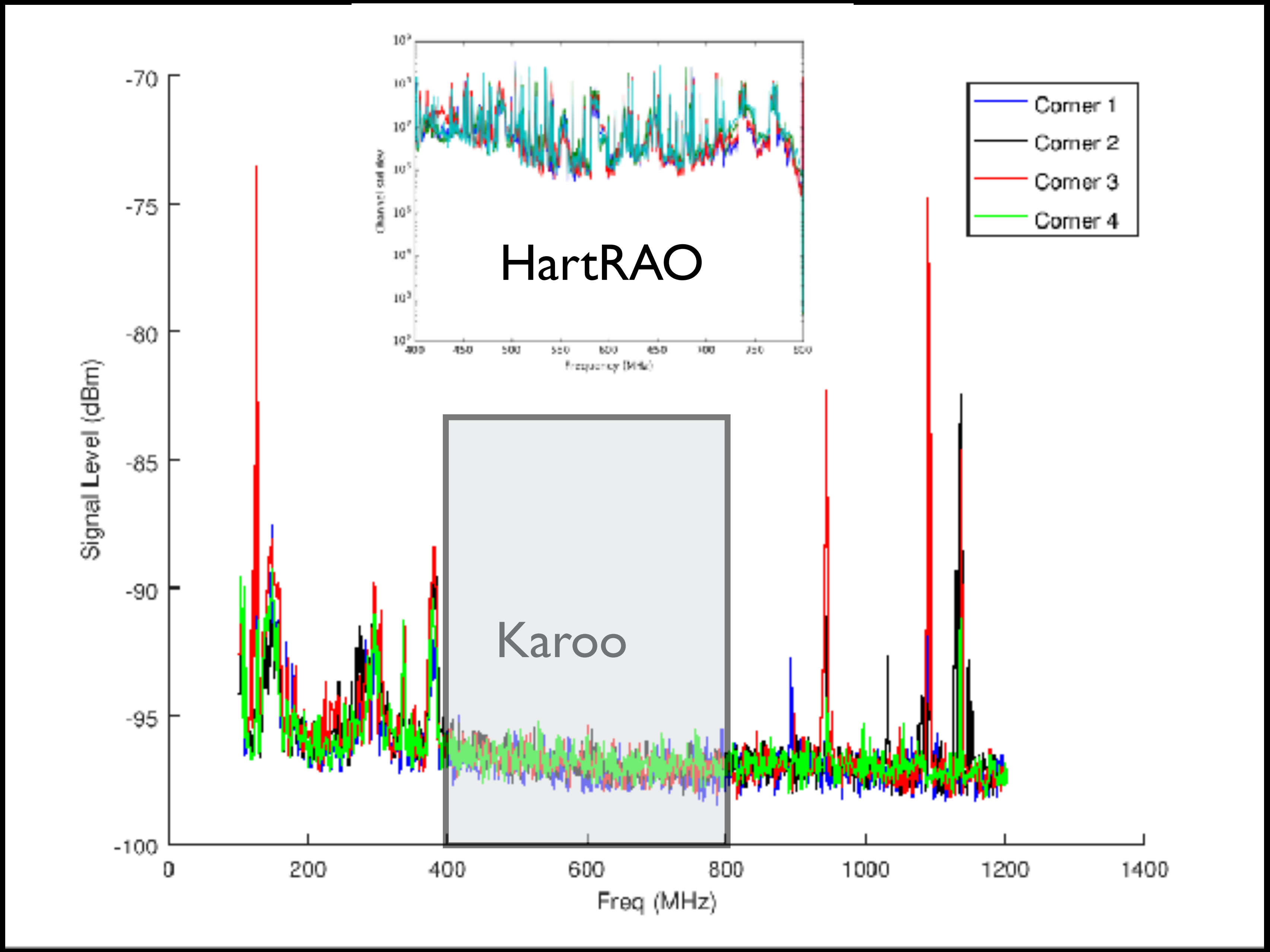
HIRAX Design Plan (set by intensity mapping) perfect for FRBs

- Order 10^3 close-packed 6m dishes.
- Operate between 400-800 MHz
- 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…
- 9x Parkes area, ~50x FOV means many, many more FRBs. Up to ~20 per day (with huge error bar)

HIRAX Site

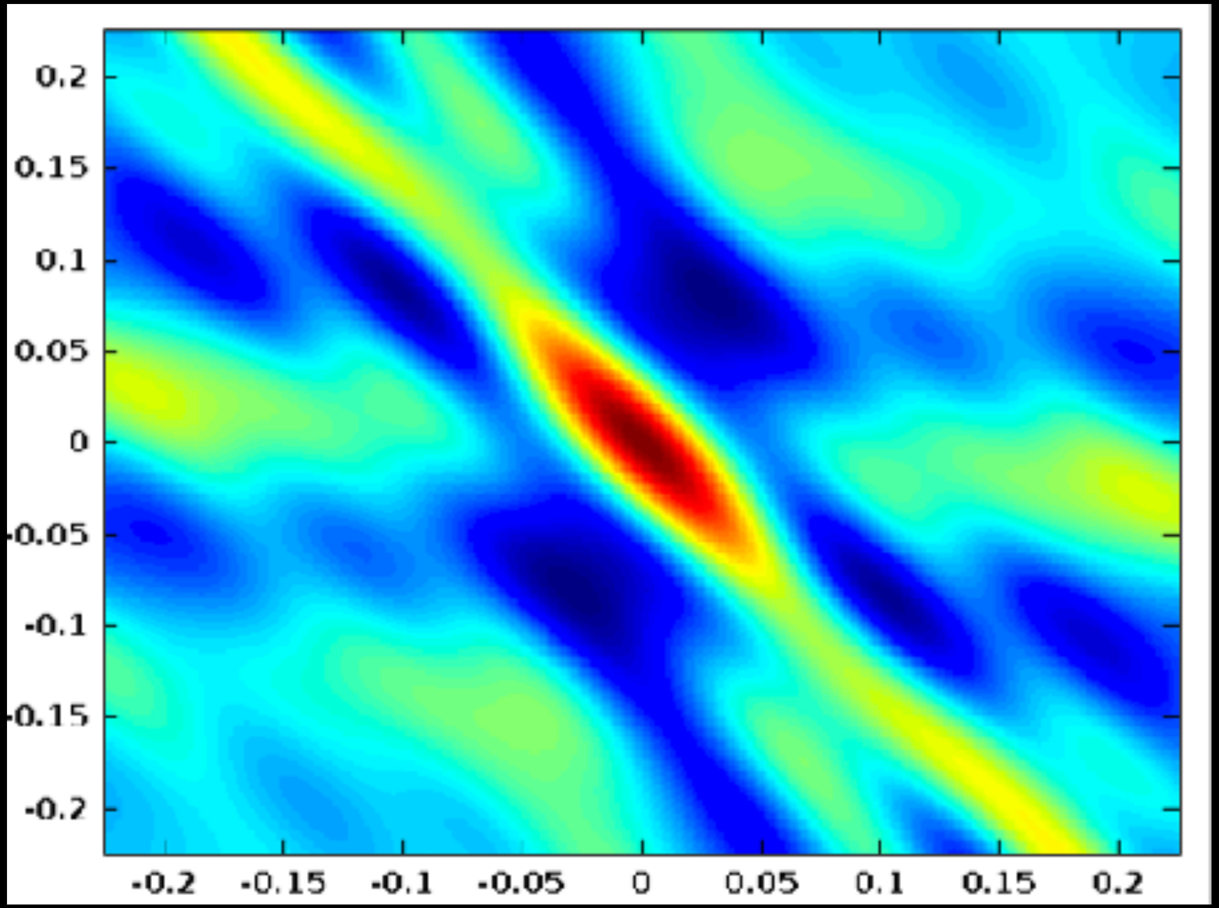


RFI tests at HIRAX site in Karoo (final approval received). Conditions look spectacular! Plus bonus aardvark…



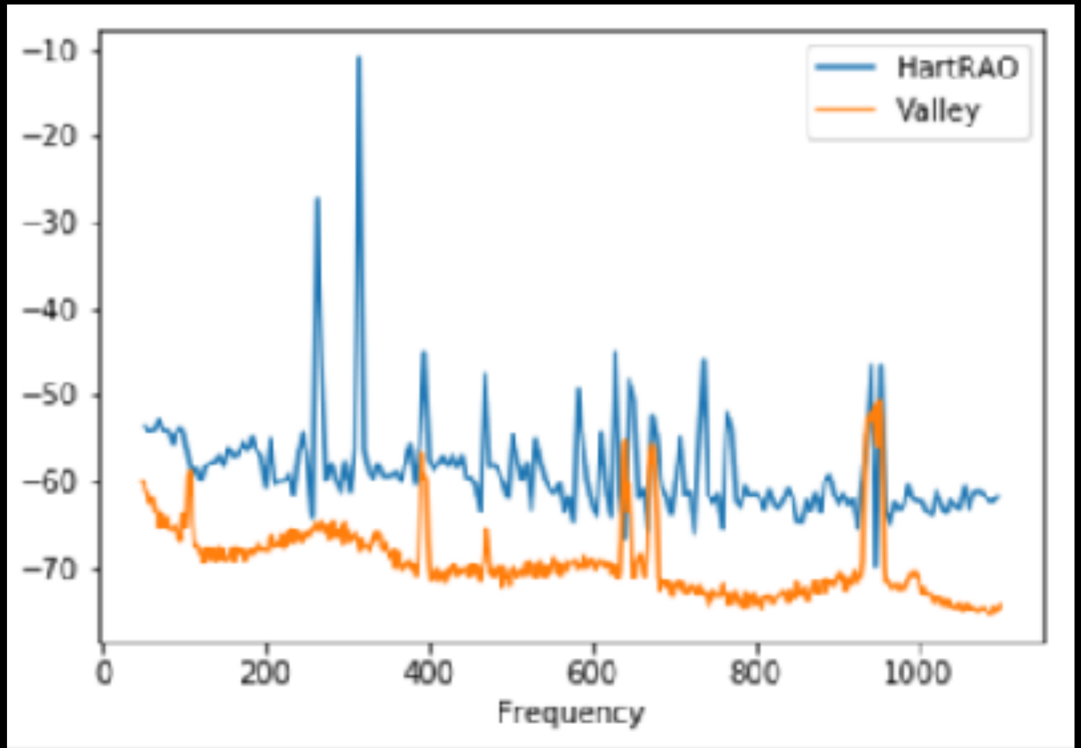
Outriggers

- With outriggers, can get VLBI positions for HIRAX events. 6m dishes easy to replicate.
- 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.



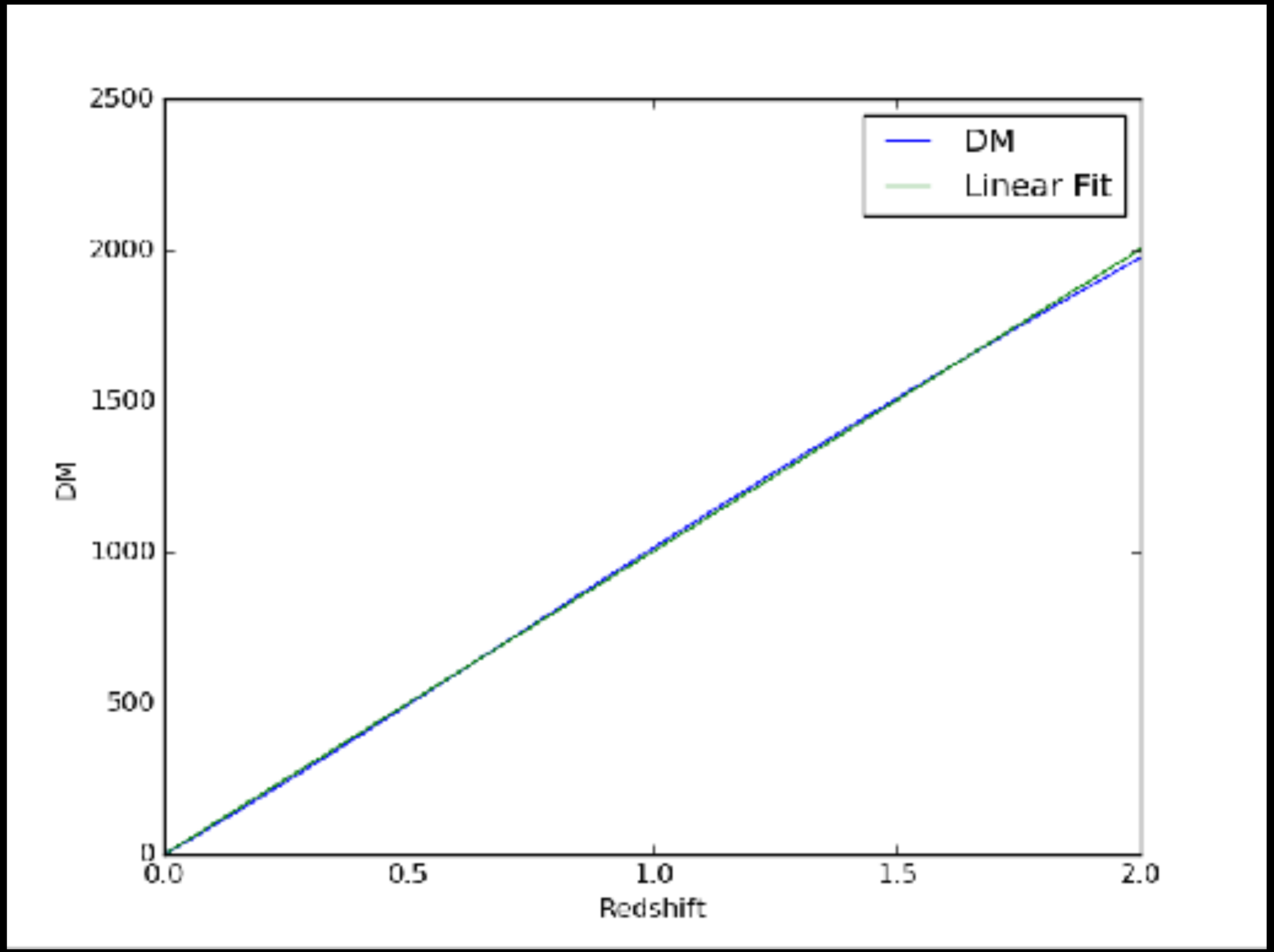
- ~1000 km baselines
- resolution ~100 mas, centroiding to few 10s of mas
- Red: funded/under construction. Yellow: proposed (Botswana, Durban)/advanced discussions. AIMS-Rwanda will also host outrigger. Blue: desirable
- Bottom: beam from red+yellow for flat-spectrum FRB. Plot axis in arcseconds (typical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

Site Testing at BIUST



What Might we do with FRBs?
(aside from figuring out what they are)

- FRBs give us exquisite arrival time information across possibly wide frequency bands.
- FRBs give us exquisite (1/(1+z)-weighted) electron column density measurements.
- $DM_{obs}=DM_{MW}+DM_{IGM}+DM_{host}$. Handy rule, $z \sim DM_{IGM}/1000f_{ion}$.
- Contribution from host uncertain, but distances are likely cosmological (FRBs noticed because DM too high to come from Milky Way).
- Could serve as probes where this information is useful.
- Careful examination of FRB signals can sometimes unlock other information…



LOCATING THE “MISSING” BARYONS WITH EXTRAGALACTIC DISPERSION MEASURE ESTIMATES

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Received 2013 September 17; accepted 2013 December 4; published 2013 December 19

- With many FRBs with locations and redshifts, stack on l.o.s. haloes.
- Observed DM should deviate from mean level based on column density from intervening halo. i.e. get a “bump” in DM from halo contribution.
- McQuinn key finding: ~100 FRBs at z~0.5 with arcminute positions enough constrain missing baryons.

Photon mass limits from fast radio bursts

We dedicate this paper to the memory of Lev Okun, an expert on photon mass

Luca Bonetti [a, b], John Ellis [c, d], Nikolaos E. Mavromatos [c, d], Alexander S. Sakharov [e, f, g], Edward K. Sarkisyan-Grinbaum [g, h], Alessandro D.A.M. Spallicci [a, b]

- If photons are massive, low energy moves slower than high.
- Single event, DM degenerate with mass. Still gives limits of few 10^{-14} eV.
- Down the road, DM(z) and delay(z) from mass behave differently - will allow degeneracy breaking.
- NB - current lab limit is 10^{-14}, so FRBs will do better. Existence of galactic-scale magnetic fields implies (much) lower mass limit, but is far less direct.

Testing Einstein's Equivalence Principle with Fast Radio Bursts

Jun-Jie Wei[1], He Gao[2], Xue-Feng Wu[1,3*], and Peter Mészáros[4,5,6]

LIMITS ON EINSTEIN'S EQUIVALENCE PRINCIPLE FROM THE FIRST LOCALIZED FAST RADIO BURST FRB 150418

S. J. Tingay[1] and D. L. Kaplan[2]

- If FRB photons emitted inside potential well, violations of equivalence principle would lead to frequency-dependent arrival shifts.
- Single event limits of $\sim 10^{-9}$ expected, possibly better with DM models.

PROBING WHIM AROUND GALAXY CLUSTERS WITH FAST RADIO BURSTS AND THE SUNYAEV–ZEL'DOVICH EFFECT

YUTAKA FUJITA[1], TAKUYA AKAHORI[2], KEIICHI UMETSU[3], CRAIG L. SARAZIN[4], AND KA-WAH WONG[5,6]

- Optical depth through rich cluster is 0.01. Means DM is 5000(!)
- FRB that goes off behind cluster tells you τ, possibly to 5% or better.
- TSZ measurement then tells you mass-weighted temperature
- Very clean measurement, does not rely on X-rays
- Does require many, many FRBs

Cosmology with kSZ: breaking the optical depth degeneracy with Fast Radio Bursts

Mathew S. Madhavacheril,[1] Nicholas Battaglia,[2,3] Kendrick M. Smith,[4] and Jonathan L. Sievers[5,6]

- kSZ is major goal of upcoming CMB experiments.
- kSZ sensitive to growth of structure, hence e.g. neutrino mass.
- kSZ measures velocity (good! cosmology lives here!) times electron density (bad! full of uncertainties!)
- FRBs directly measure electron column density, with uncertainty from FRB host contribution.

Cosmology with kSZ: breaking the optical depth degeneracy with Fast Radio Bursts

Mathew S. Madhavacheril,[1] Nicholas Battaglia,[2,3] Kendrick M. Smith,[4] and Jonathan L. Sievers[5,6]

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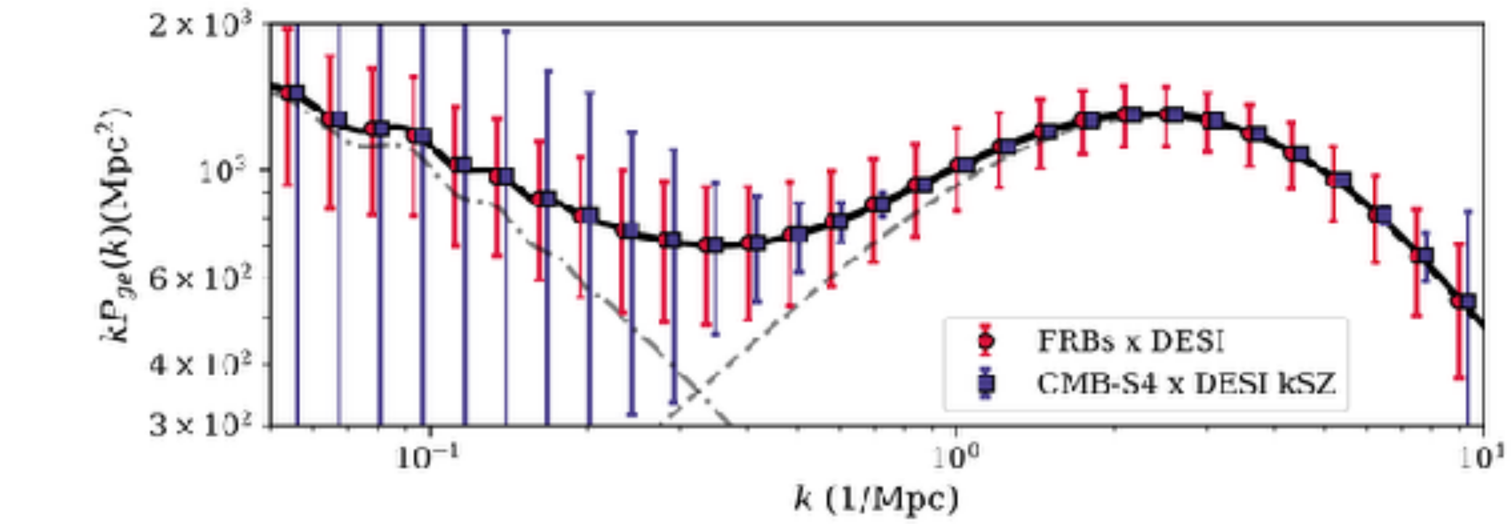

FIG. 2: The cross-power-spectrum of galaxies and electrons as measured either through kSZ tomography with CMB-S4 and DESI (blue) with fixed cosmology, or through cross-correlation of dispersion measures of 10^4 FRBs with DESI galaxies (red), where the RMS scatter of DMs is assumed to be 300 $\frac{pc}{cm^3}$. FRB DMs measure the power over a broad range of scales including the 2-halo regime (dot-dashed), while kSZ tomography provides an extremely tight measurement in the 1-halo dominated regime (dashed).

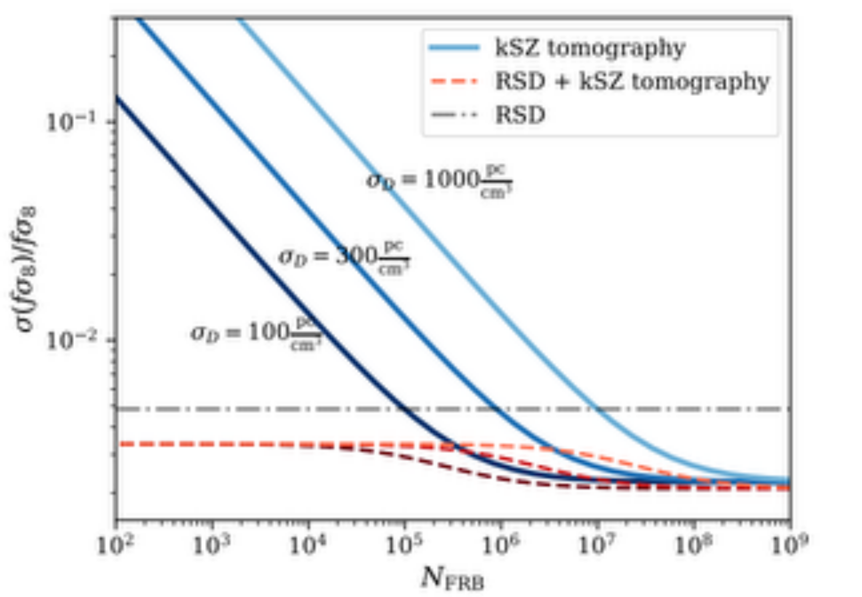

FIG. 4: The uncertainty on the combination of cosmic growth rate and amplitude of matter fluctuations $f\sigma_8$ from kSZ tomography with CMB-S4 and DESI as a function of the number of FRBs, N_{FRB}, available to break the 'cluster optical depth degeneracy' through cross-correlation of FRB DMs with the same DESI galaxy sample. The blue lines show the constraint from kSZ tomography with various shades corresponding to choices of the uncertain RMS scatter of FRB DMs σ_D. If RSD information is used in conjunction with kSZ (red dashed lines), the degeneracy is already broken to some degree but further improvement is possible with FRBs. The grey dot-dashed line shows the constraint from DESI RSD alone.

With 10^4 FRBs with localizations, can improve on galaxy-electron xcorr on large scales over S4+DESI (above)

Improves on cosmology over S4+RSD for ~10^6 FRBs (right).

FRB rate ~$A^{1.5}$, so a few times HIRAX capable of reaching 10^6 FRBs on decade timescale

Strongly lensed repeating fast radio bursts as precision probes of the universe

Zheng-Xiang Li, He Gao, Xu-Heng Ding, Guo-Jian Wang & Bing Zhang

Lensing of Fast Radio Bursts as a Probe of Compact Dark Matter

Julian B. Muñoz,[1] Ely D. Kovetz,[1] Liang Dai,[2] and Marc Kamionkowski[1]

- Build a (set of) telescopes that observe along a large range in RA at fixed dec?
- Time delays will be exquisitely measured (usual microlensing caveats will apply)
- Unclear, but entirely possible there exist several strongly lensed FRBs per day available to us.

Think Big!

- FRBs are a new window on universe - what else can one do with them?
- Assuming most FRBs don't repeat, getting to millions of localized FRBs does not require new technology, and can be done in finite amounts of money.
- I firmly believe there's a lot of space for new ideas.
- If you convince us we can do something cool with lots of FRBs, we can (probably) find them.

Conclusions

- Fast radio bursts are true enigmas.
- While event rate started slow, instruments like CHIME, ASKAP are hugely upping discovery rate.
- HIRAX will find order 10^4 FRBs, large fraction with localizations.
- Can use FRBs as cosmological probes, with impacts in baryon distribution, fundamental physics, lensing…
- Think of new uses for them!