The Fast Radio Burst population as observed by ASKAP

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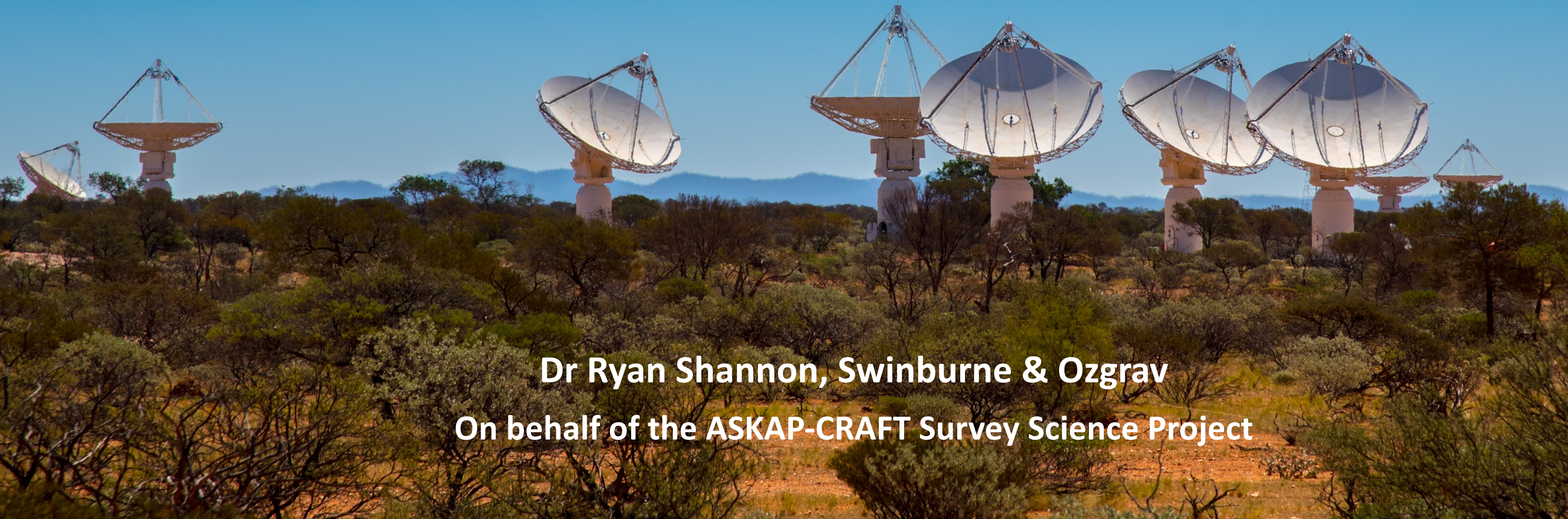


Dr Ryan Shannon, Swinburne & Ozgrav

On behalf of the ASKAP-CRAFT Survey Science Project

Overview

- Fast radio bursts
- ASKAP + CRAFT
- The fly's eye survey
- Special snowflakes
- Connection to other FRB populations
- Breaking news from Parkes
- No twitter, please

CRAFT:

Commensal Realtime ASKAP Fast Transient Survey
PIs: K. Bannister, J.-P. Macquart, R. M. Shannon
CASS/Curtin/Swin/UCSC/USyd++

dit: Mia Walker (ICRAR-Curtin)

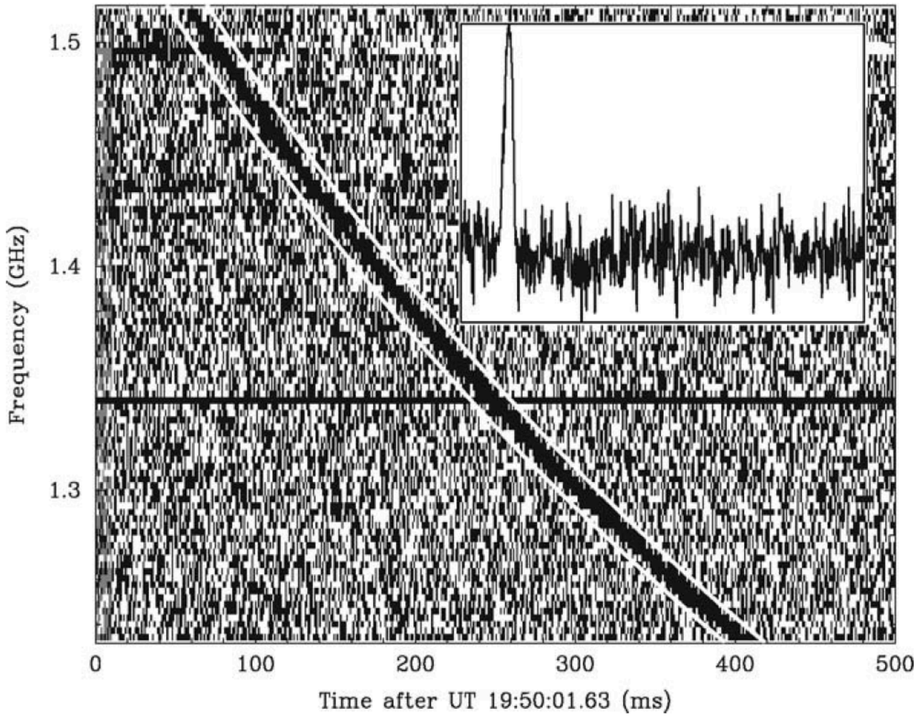
Fast Radio Bursts (FRBs)

- Discovered in pulsar surveys with the Parkes telescope as highly dispersed, short, bright single pulses of radio emission
  - High Galactic latitudes
  - Dispersion measure (DM) well in excess of any credible model of Milky Way DM
  - Very good agreement with t ~ frequency^{-2}
  - Some show evidence for being broadened by scattering

- No definitive emission mechanism
  - Cosmological (Gamma-ray bursts?)
  - Galactic (flare stars?)
  - Terrestrial (lightning?)
  - Anthropogenic (RFI?)

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,[1,2]* M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]



Fast Radio Bursts (FRBs)

- Frequent
  - 2000 – 6000 per day over the entire sky at Parkes sensitivity levels
  - Difficult to associate with other classes of known transient
  - Measure brightness in integral units of “fluence”
    - Jansky-millisecond

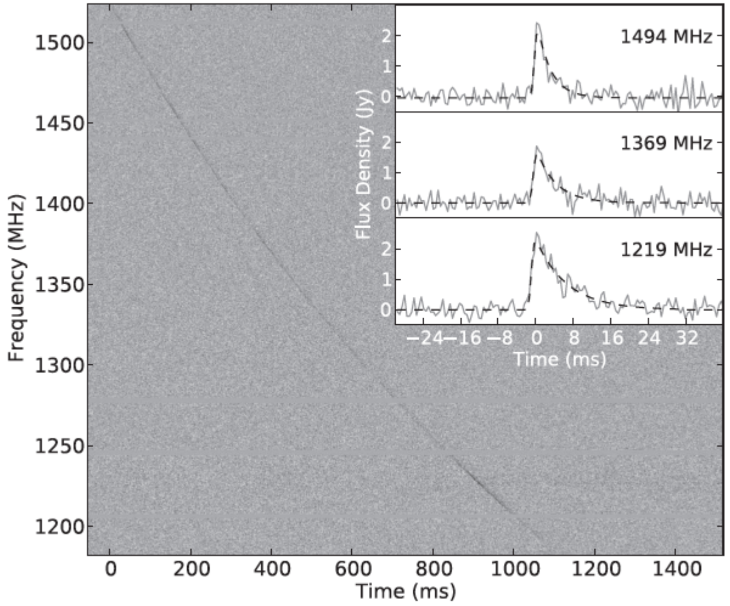
- Rarely detected given limited field of view of current telescopes (1 per 10 days of observing with Parkes)

- **Why care?**
- Represent a new unusual class of (coherent) radio emission
- If cosmological, opportunity to probe diffuse intercluster plasma
  - Sensitive to entire column density of electrons along line of sight
  - Find missing baryons (via electrons)
  - Study intergalactic plasma: (is it clustered around galaxies more more diffusely spread through space)
  - With polarisation (rotation measure), study magnetic field of Universe

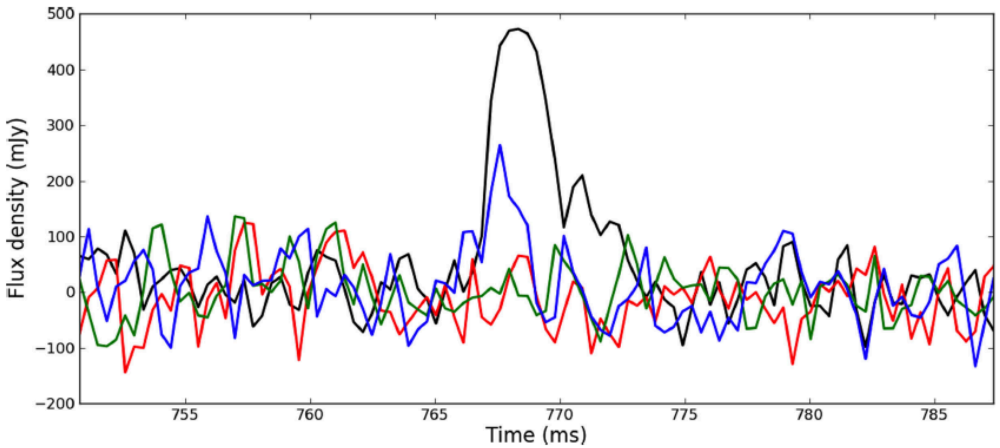
www.sciencemag.org SCIENCE VOL 341 5 JULY 2013

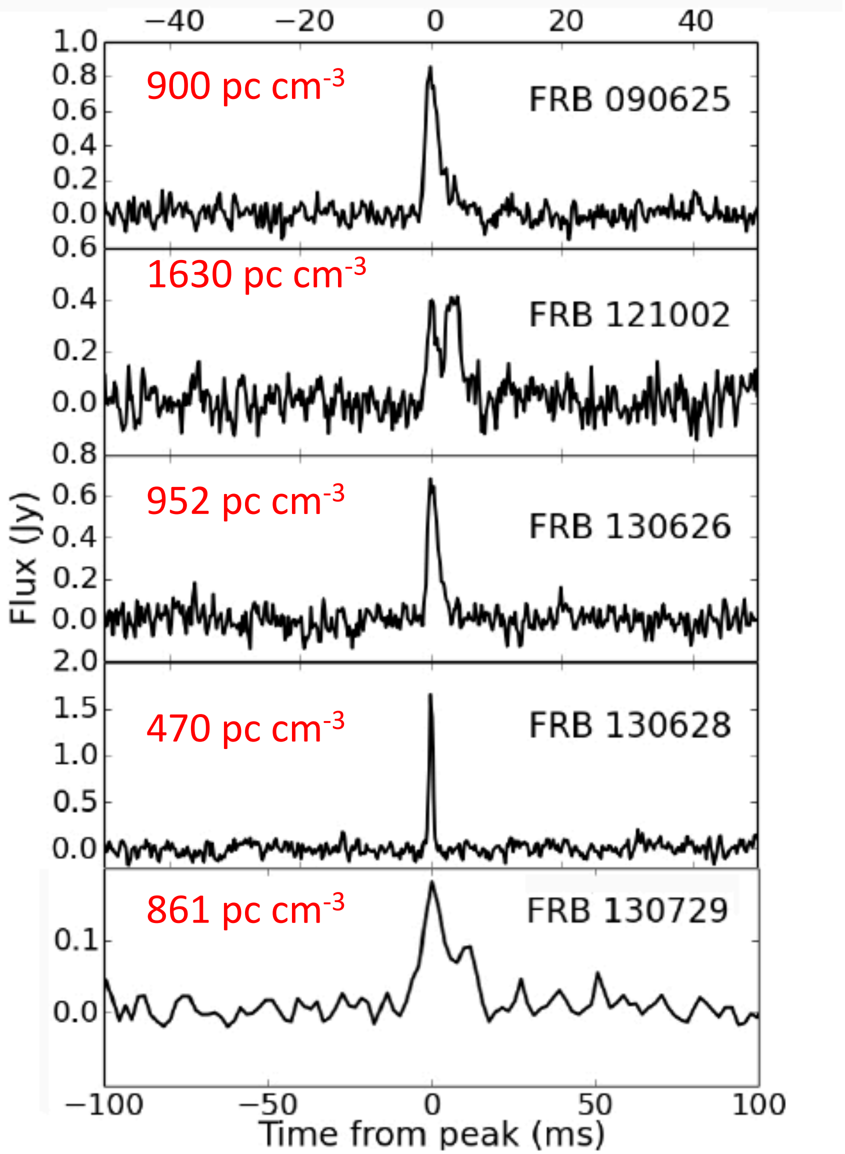
A Population of Fast Radio Bursts at Cosmological Distances

D. Thornton,[1,2*] B. Stappers,[1] M. Bailes,[3,4] B. Barsdell,[3,4] S. Bates,[5] N. D. R. Bhat,[3,4,6] M. Burgay,[7] S. Burke-Spolaor,[8] D. J. Champion,[9] P. Coster,[2,3] N. D'Amico,[10,7] A. Jameson,[3,4] S. Johnston,[2] M. Keith,[2] M. Kramer,[9,1] L. Levin,[5] S. Milia,[7] C. Ng,[9] A. Possenti,[7] W. van Straten[3,4]



The FRBs as seen by Parkes

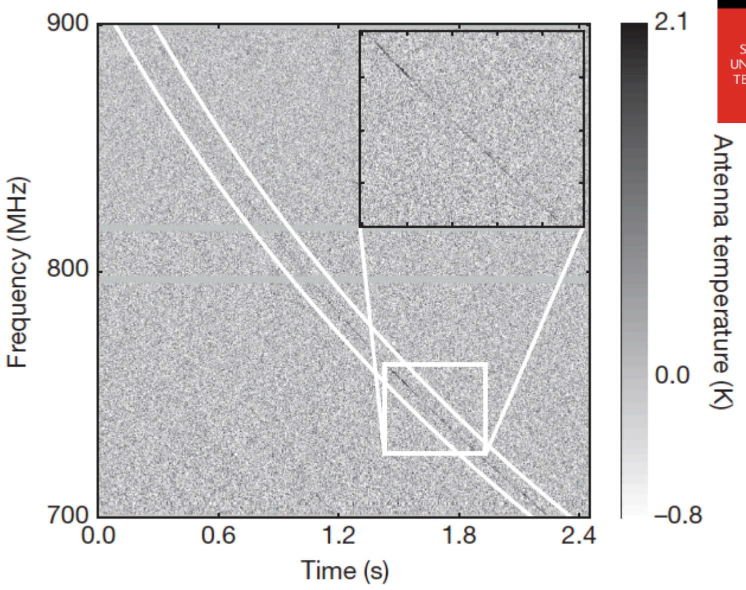


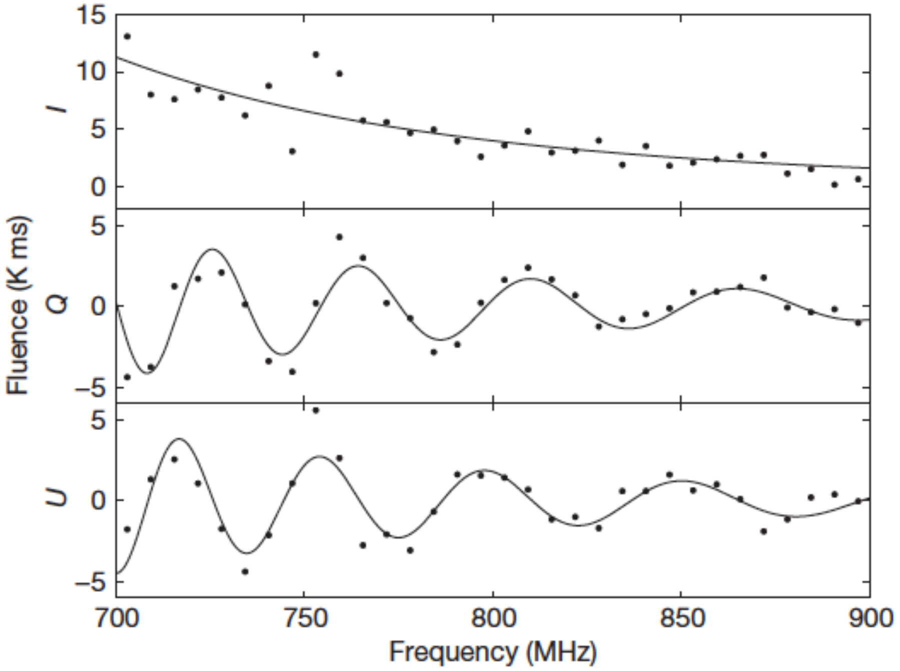


- Larges surveys conducted with 64-m Parkes radio telescope/ 20cm multibeam system
- BPSR backend: upgraded system designed to see bursts in "hi-fi"
- High Time Resolution Universe Survey and other bespoke searches
    - Search for bursts in real time
- Variable widths and levels of scattering
- Evidence for polarisation
- One with "double pulse"

FRBs beyond beyond 1400 MHz

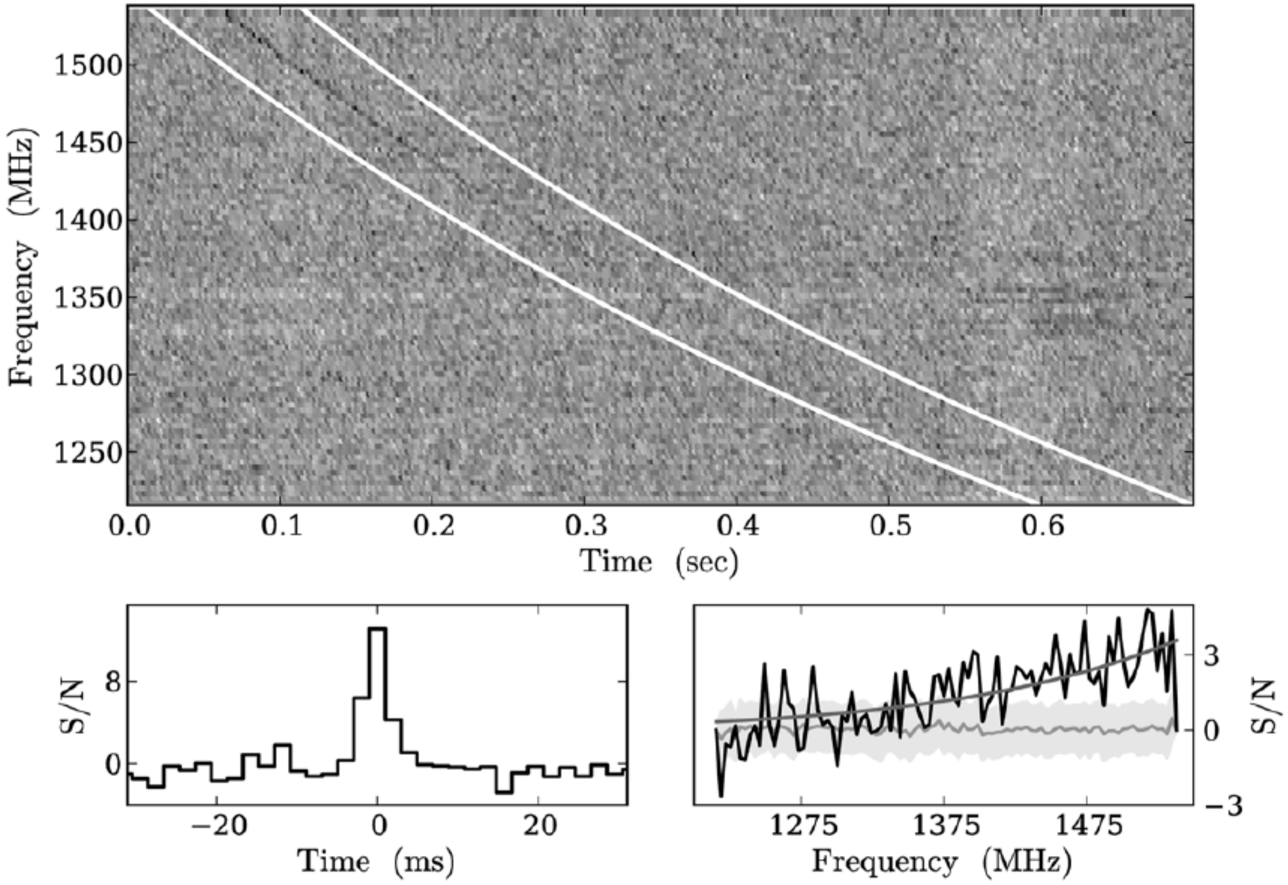
- FRB detected with Green-bank telescope at 800 MHz (30 cm)
  - FRB 110523 (Masui et al. 2015)
- Detected in processing of HI intensity mapping experiment
- Shows strong linear polarisation
- In contrast, others shows strong circular polarisation (Petroff et al. 2015)
- High RM -> significant host contribution to electron column density





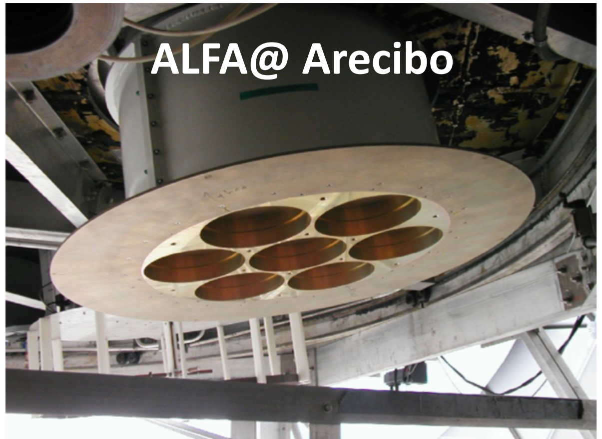
FRBs beyond Parkes

- Arecibo FRB 121102
  - Spitler et al. 2014
- Detected in Pulsar ALFA survey
  - ALFA – 7 beam equivalent to Parkes multibeam system
  - 0.4 Jy peak flux
  - Inverted spectrum: instrumental effect?
- Galactic plane, but anti-centre
- Only 2x galactic DM
  - No reason to expect overdensity of plasma along this line of sight



Challenges with single dish searches

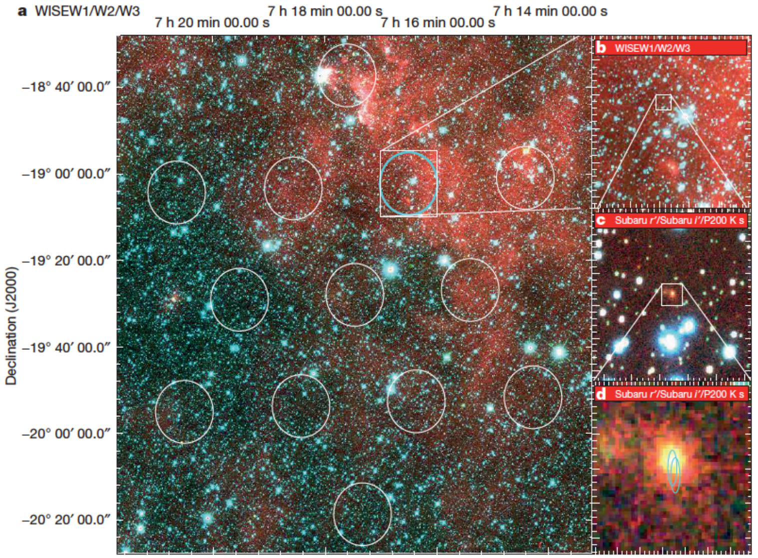
- Poor localization due to receiving system
  - Single element (GB)
  - Sparsely sampled focal planes (Parkes, Arecibo)
  - Uncertain location within beam pattern (0.25 deg for Parkes)
- Consequences
  - Uncertainty about burst attenuation/implied brightness
  - Unable to determine unique host (star/galaxy/etc.)
- Localize in real time
  - Real time searches
  - Look for transients at other wavelengths



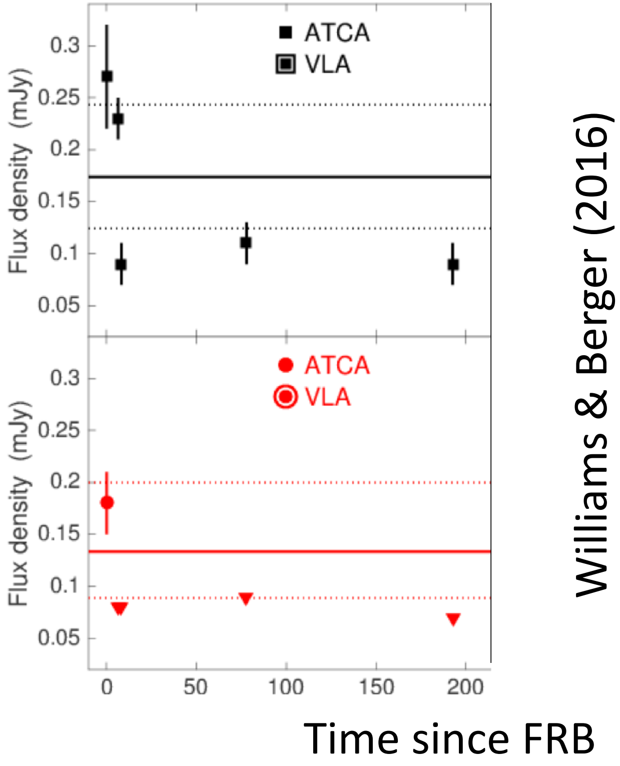
An FRB with an afterglow

FRB 150418 (Keane et al. 2016)

- Fading radio source discovered with ATCA and coincident and contemporaneous with FRB
- Host galaxy of radio afterglow identified (z ~ 0.5)
- Consistent with DM-*z* relationship
  - “solved” missing-Baryon problem



Keane et al. (2016)



Williams & Berger (2016)

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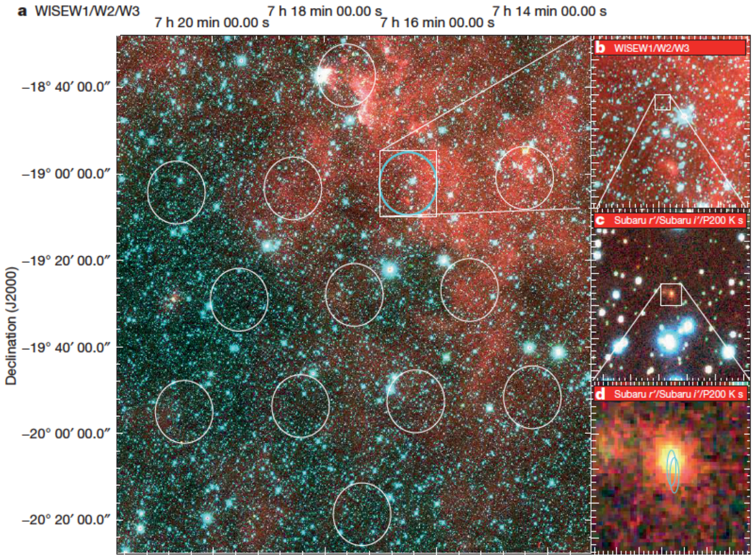
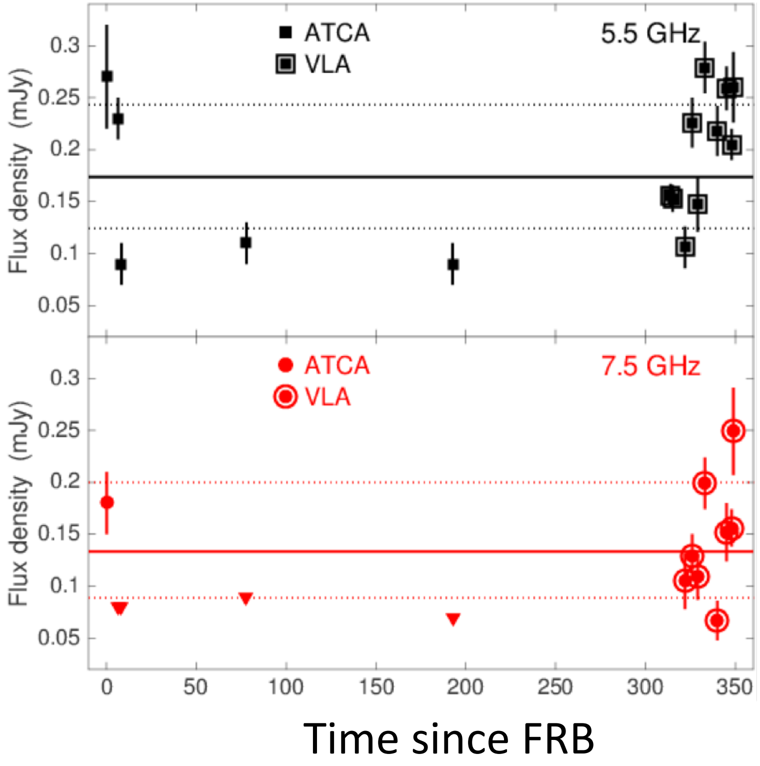
- Fading radio source discovered with ATCA and coincident and contemporaneous with FRB
- Host galaxy of radio afterglow identified (z ~ 0.5)
- Consistent with DM-*z* relationship
  - “solved” missing-Baryon problem
- Subsequent observations have shown that source has re-brightened
  - Intrinsic variability?
  - Scintillation

- Even if not associated, an unusual transient



Keane et al. (2016)



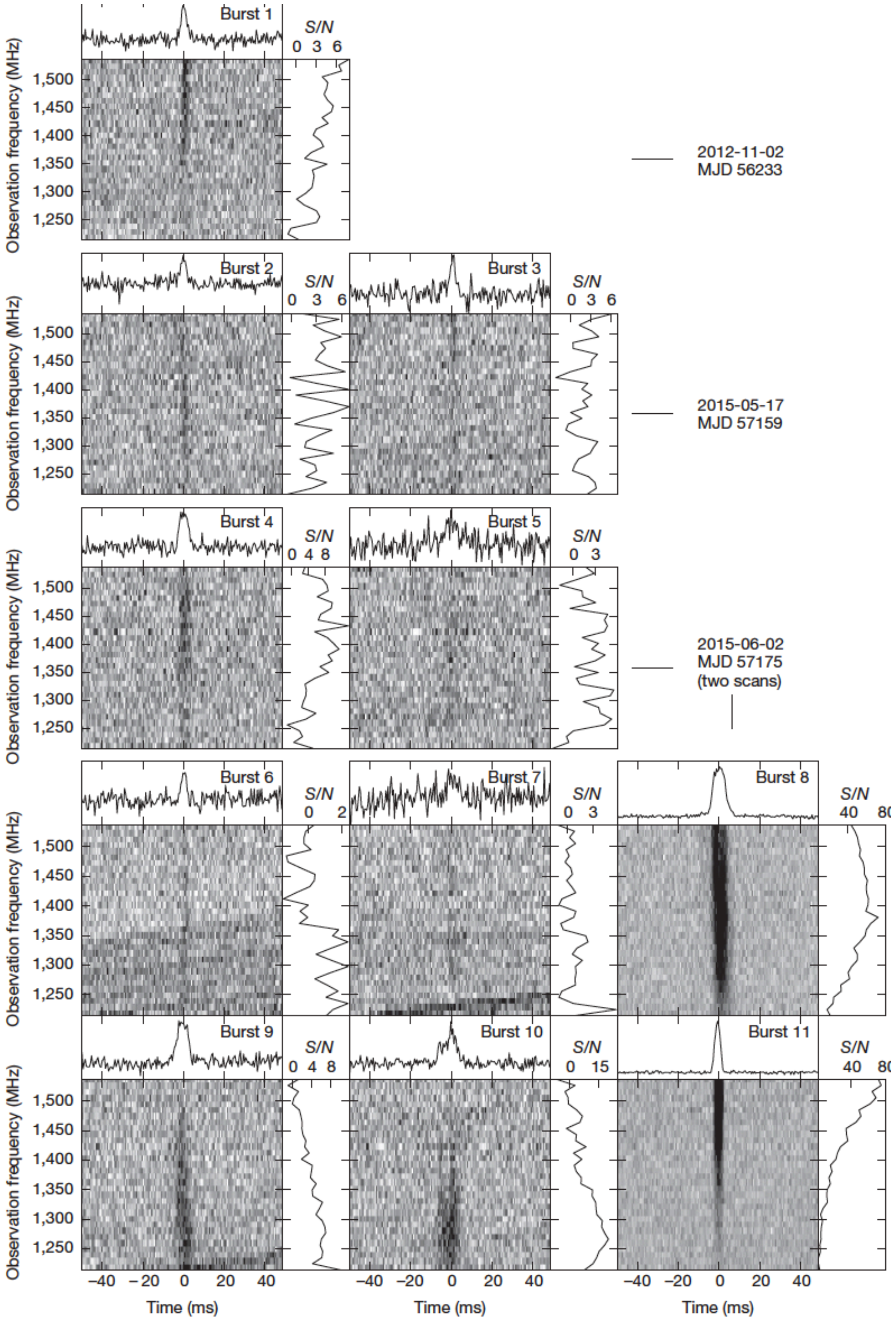
Williams & Berger (2016)

A repeating FRB source

Continued monitoring of the Arecibo FRB (121102): detections of repeat pulses (Spitler et al. 2016)

- Wildly variable spectral index
- No obvious periodicity in the pulses
  - Fast rotation?
  - Magnetar-like emission?

- Enables follow up with interferometers
  - Arcsecond position: unique host identification



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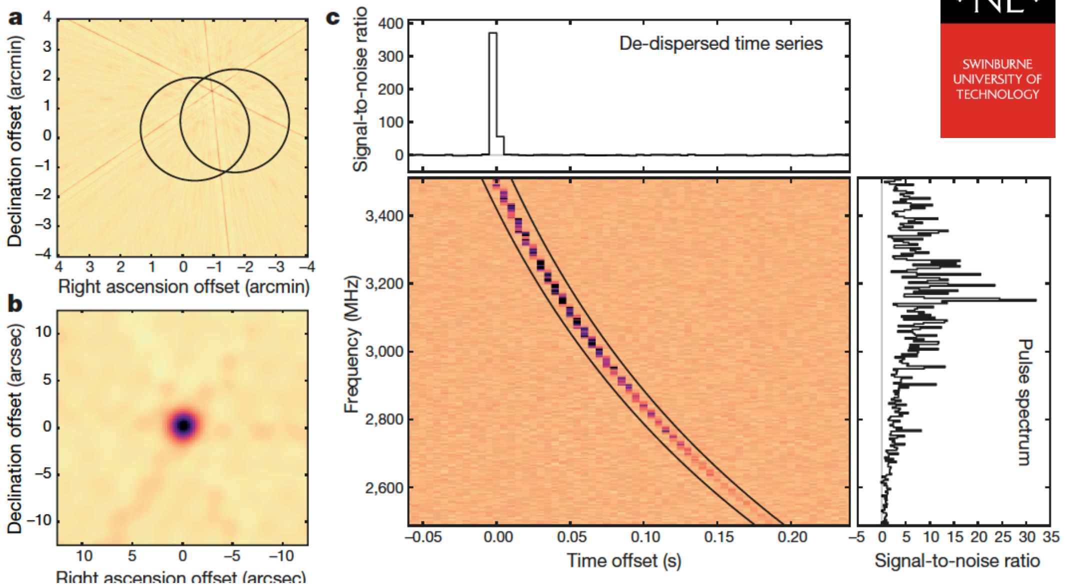
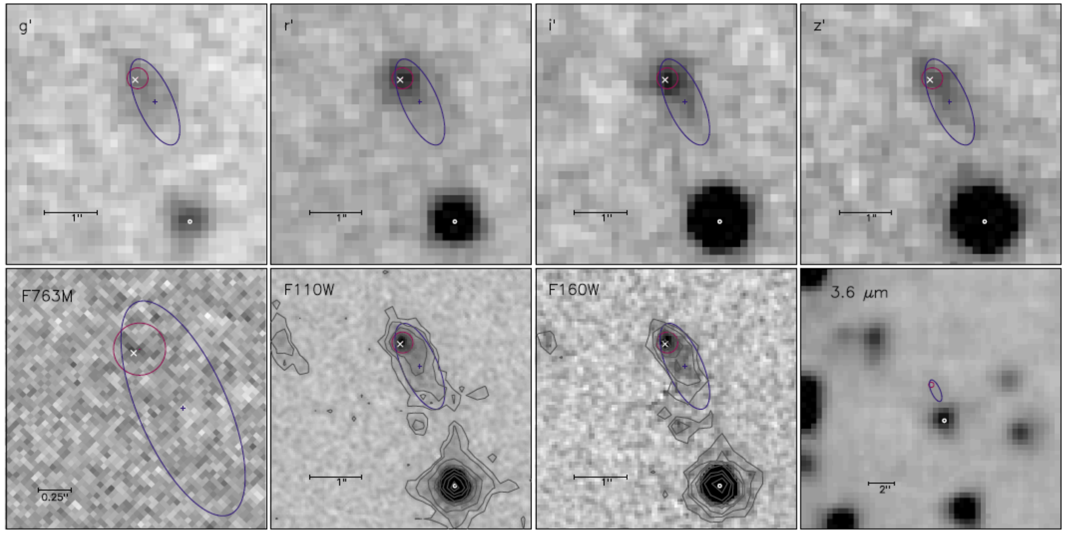
The repeater: localized

- Follow up observations with radio interferometers (VLA, EVN)

- Identified to reside in dwarf galaxy at redshift z~ 0.2 (Chaterjee et al. 2017)
  - Coincident with unusual radio nebula (Marcote et al. 2017)
    - AGN/supercharged supernova remnant
  - Within H-alpha emission region (Bassa et al. 2017)
- Association with magnetar/superluminous supernova/long gamma-ray bursts?



Chatterjee et al. (2017)

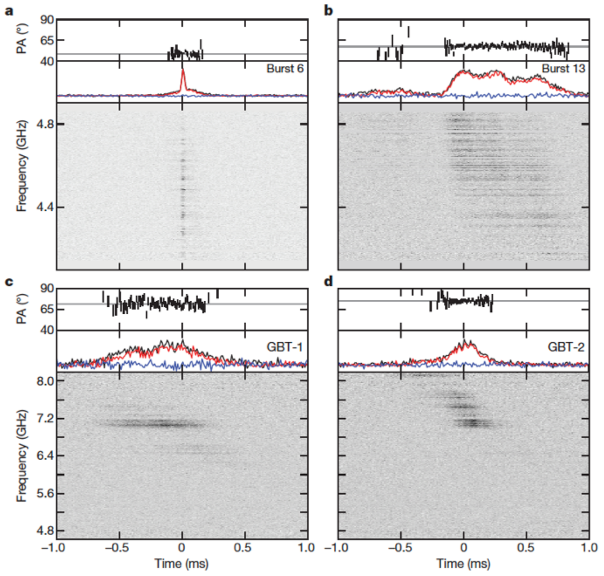


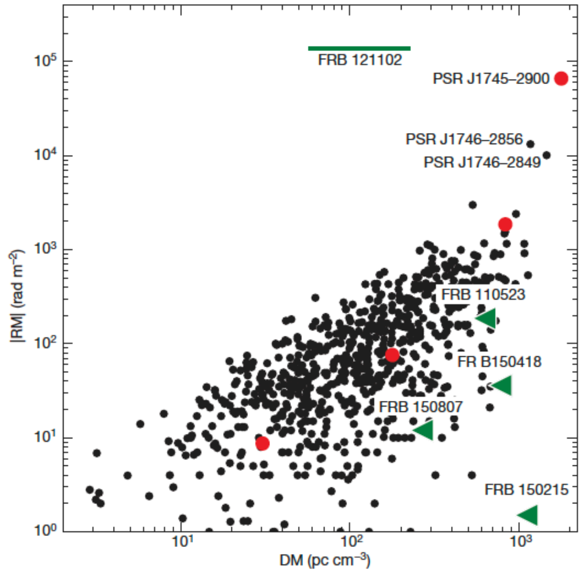
Bassa et al. (2017)

The repeater: magnetized

- Faraday rotation expected for radio waves propagating through magnetized plasma
- Strength of effect proportional to product of electron density and line of sight magnetic field
- For repeating FRB: 10^5 rad m^{-2}
  - mG magnetic field strengths
  - Larger than for any pulsar in our galaxy, other FRBs with polarization
  - Only found in vicinities of supermassive black holes
  - RM variable at > 10% level
- *Is the FRB source a neutron star orbiting black hole?*

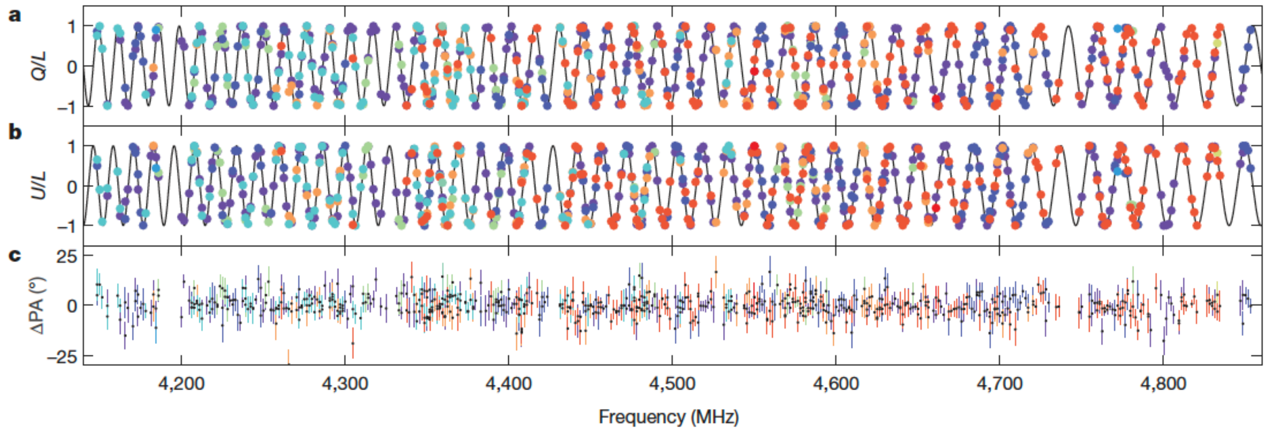
Burst profiles

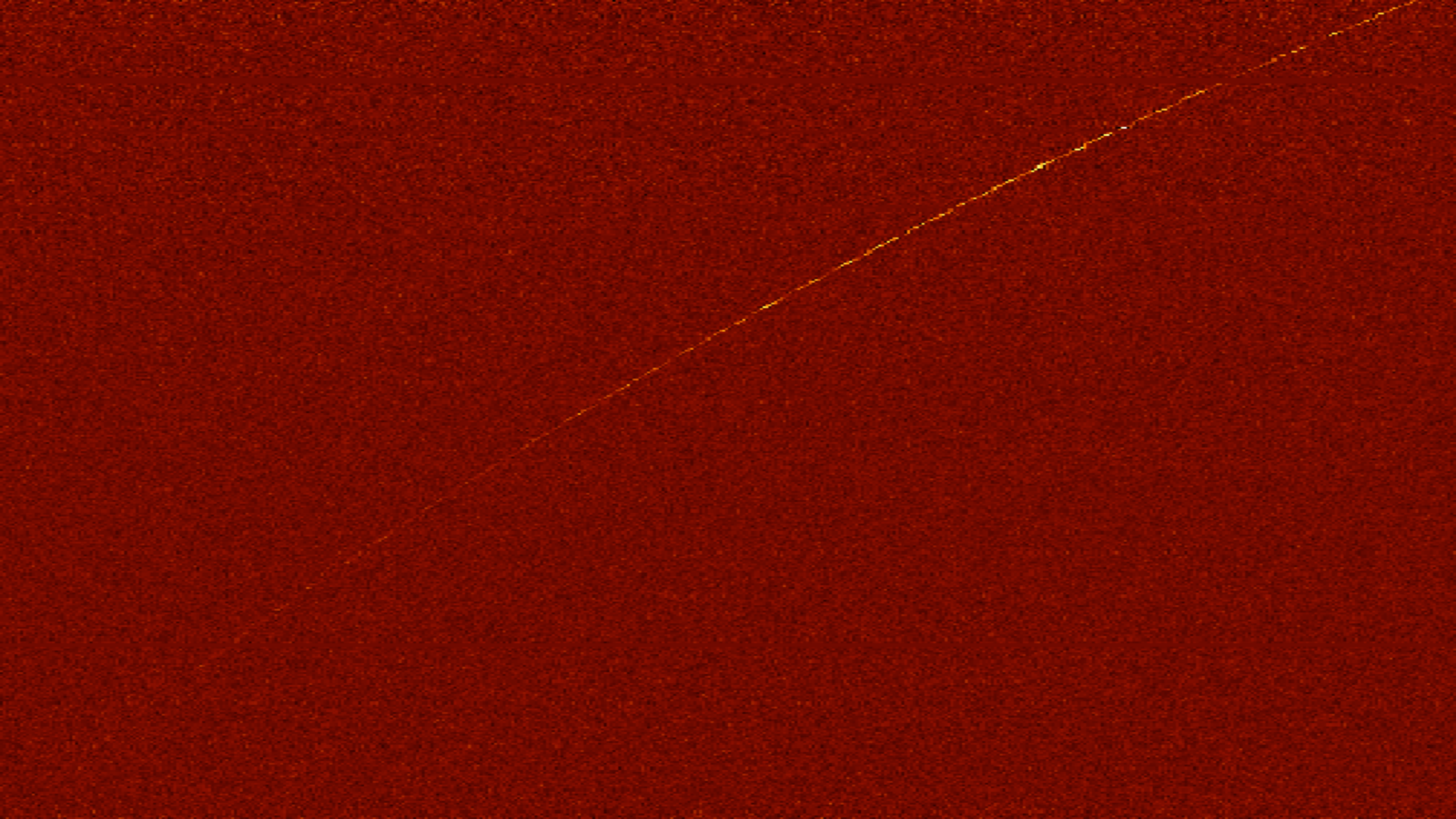




Burst polarization

Michilli et al. (2018)





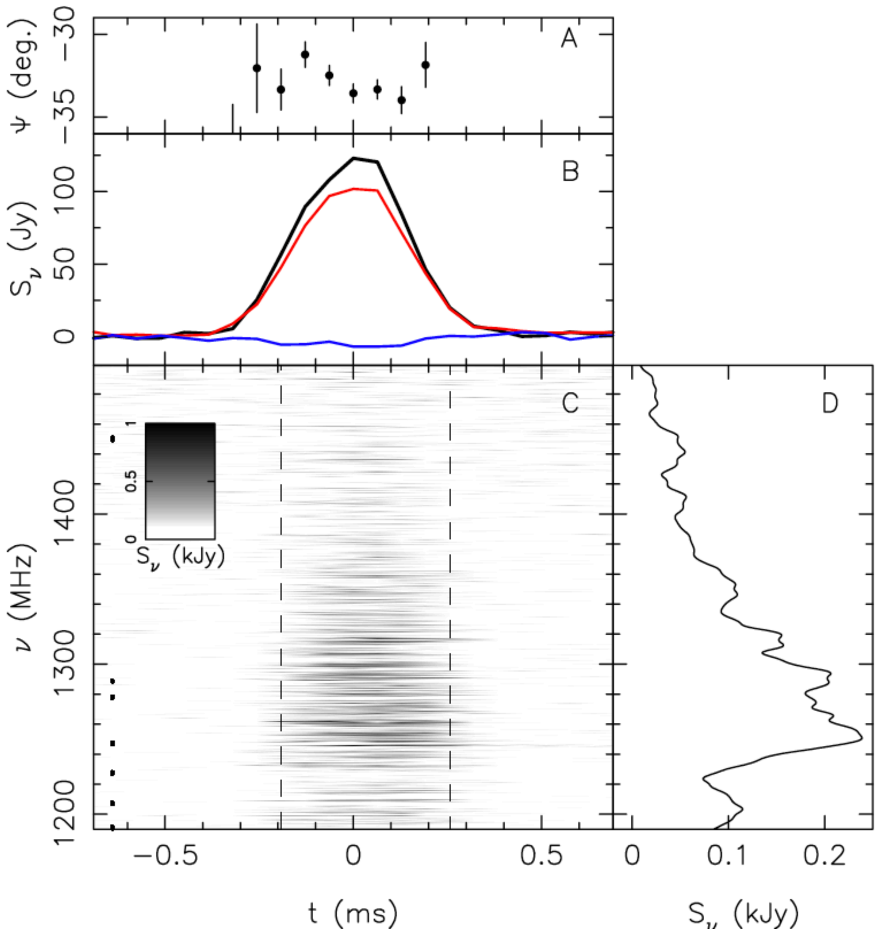
Another super-bright FRB 150807

- Discovered at Parkes while timing millisecond pulsar
- **Low DM** (for FRB)
  - 265.5± 0.1 pc cm^{-3}
  - (Pulsar in field: 11 pc cm^{-3})
- **Bright: Detected in 2 beams**
  - Good localisation (for PKS)
  - Correct for attenuation: robust flux density estimate
- **Highly linearly polarized, little Faraday rotation**
  - Extragalactic <B> field < 10 nG
- No repeat in hundreds of hours of follow up observations
- Conclusion: bright FRBs aren't rare (Ravi, Shannon et al., 2016, *Science*)

RADIO ASTRONOMY

The magnetic field and turbulence of the cosmic web measured using a brilliant fast radio burst

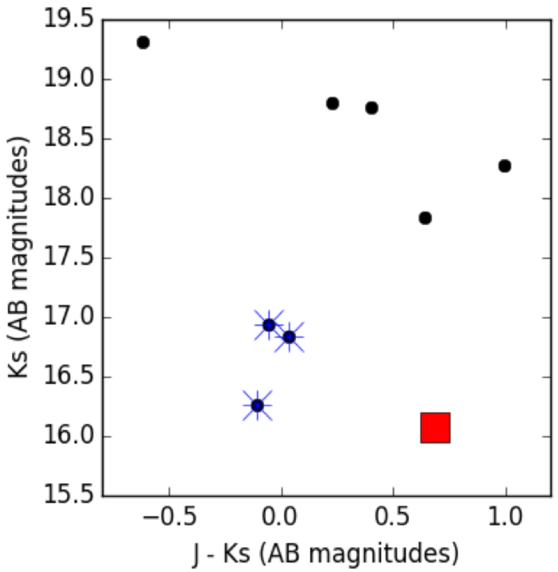
V. Ravi,[1*†] R. M. Shannon,[2,3*†] M. Bailes,[4,5] K. Bannister,[2] S. Bhandari,[4,5] N. D. R. Bhat,[3,5] S. Burke-Spolaor,[6] M. Caleb,[4,5,7] C. Flynn,[4,5] A. Jameson,[4,5] S. Johnston,[2] E. F. Keane,[8] M. Kerr,[2] C. Tiburzi,[9] A. V. Tuntsov,[10] H. K. Vedantham[1]

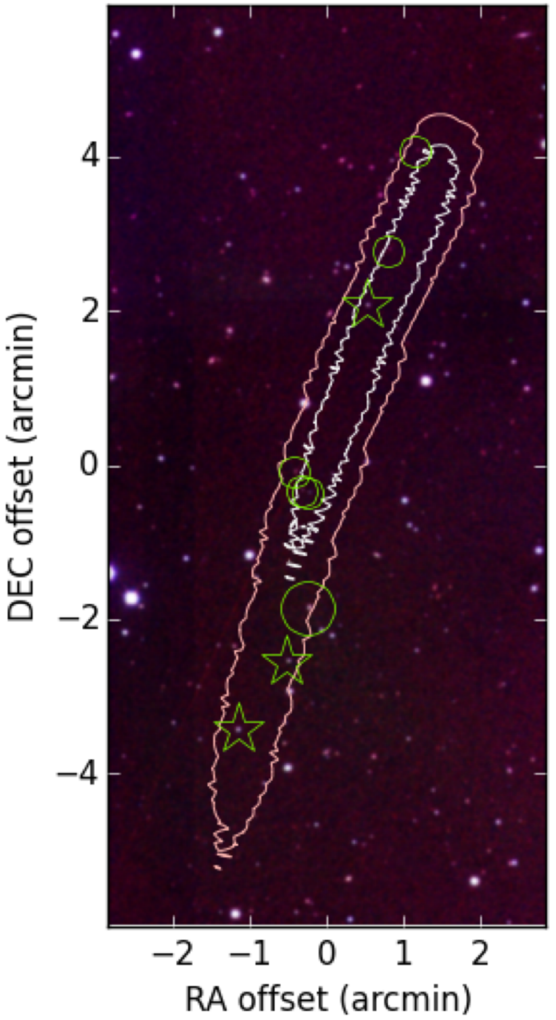


Localization of FRB 150807

- Localization region: 8x2 arcminutes

- VISTA sources (deepest optical survey of field)
  - 3 (main sequence) stars
  - 6 galaxies
  - Brightest galaxy: elliptical/lenticular
  - $z_{photo} \sim 0.2 - 0.4$
  - 95% probability that $z > 0.125$
  - Caveat: dwarf galaxies





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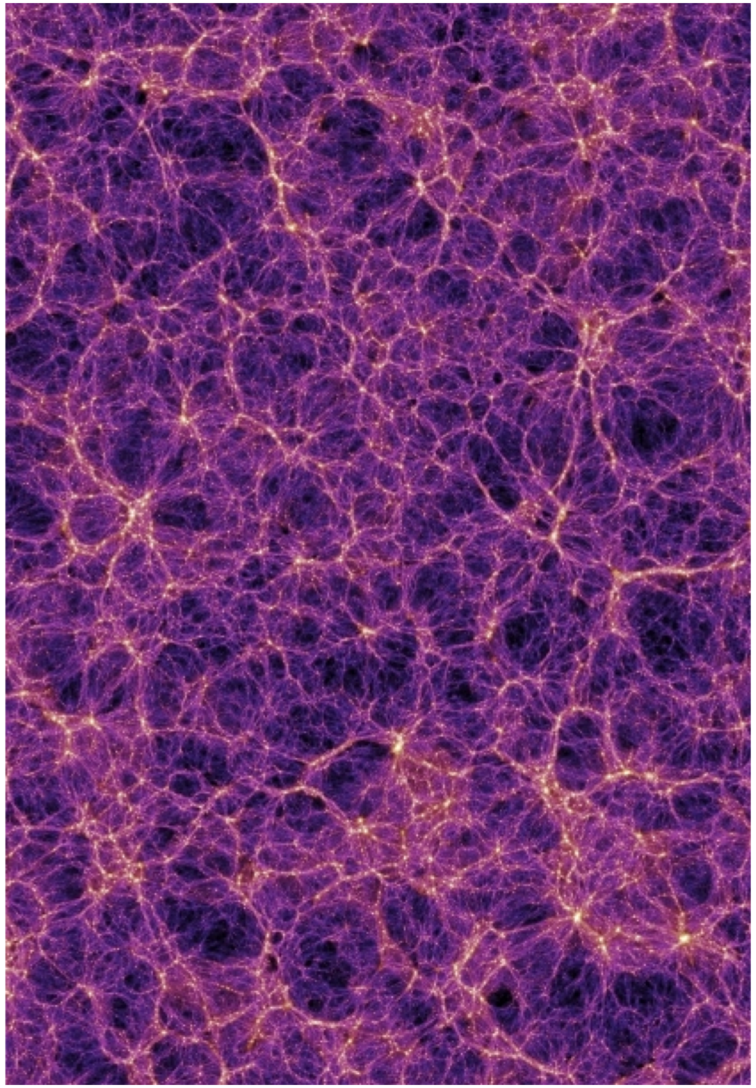
Implications for the cosmic web

- Redshift > 0.12 (distance > 500 Mpc)
  - Suggests bright FRBs occur at cosmological distances
- Low RM -> non magnetized plasma
  - $\langle B_{||} \rangle < 18$ nG

- Most of DM is extragalactic (not magnetized)
- DM consistent with z ~ 0.25
- Broadband scintillation: consistent with Galactic scattering
- Narrowband scintillation -> IGM?
  - Scattering measure (level of turbulence): 10^{-13} Gpc $m^{-20/3}$
  - In ballpark of predictions (Macquart & Koay 2013)

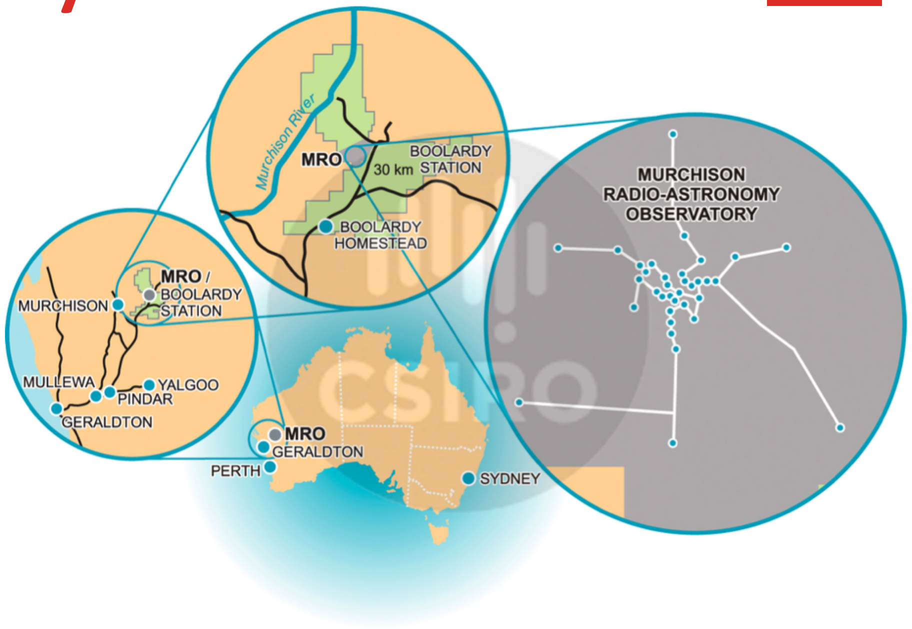


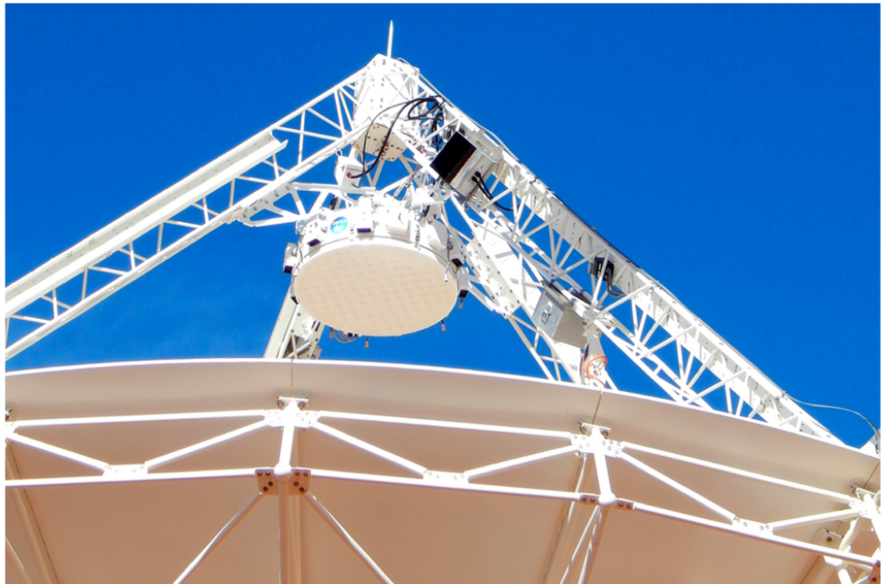
Open questions

- Are FRBs real? *Repeaters, yes. Others show significant evidence for astrophysicality*
- Do they repeat? *At least one of ~30*
- Where do they come from (local, extragalactic, cosmological)? *Extragalactic-cosmological*
- What causes them? (*Pulsars, magnetars or something more exotic?*)
- How many (gulp) classes? (*Are repeating and non-repeating FRBs caused by the same thing: Occam?*)
- Can we use them to meaningfully study the intergalactic medium? *Need to tease out host and Milky Way contributions*
- How do we find more/increase yield? (*Wide-field)*
- How unique is the (first) Lorimer burst? (*Still the brightest, but not by as much)*
  - *Significant fraction of population could be detected with smaller wider field telescopes*

Australian Square Kilometre Array Pathfinder

- Murchison Shire, Western Australia
- 36 x 12-metre antennas
- Focal plane arrays: 36 digital beams on the sky
- Each PAF: 30 deg^2 field of view
- 336 MHz available bandwidth
- Available frequency band: 0.7-1.8 GHz
- S_{sys}: 1800 Jy
- Signal path:
  - PAF (RfoF) -> Digital Receiver -> Beamformer (don't use correlator)
- Dominant sources of interference: satellites, lightning (rare), ~~chirps~~ and ~~300 Hz~~.
- Currently in commissioning and early-science phase

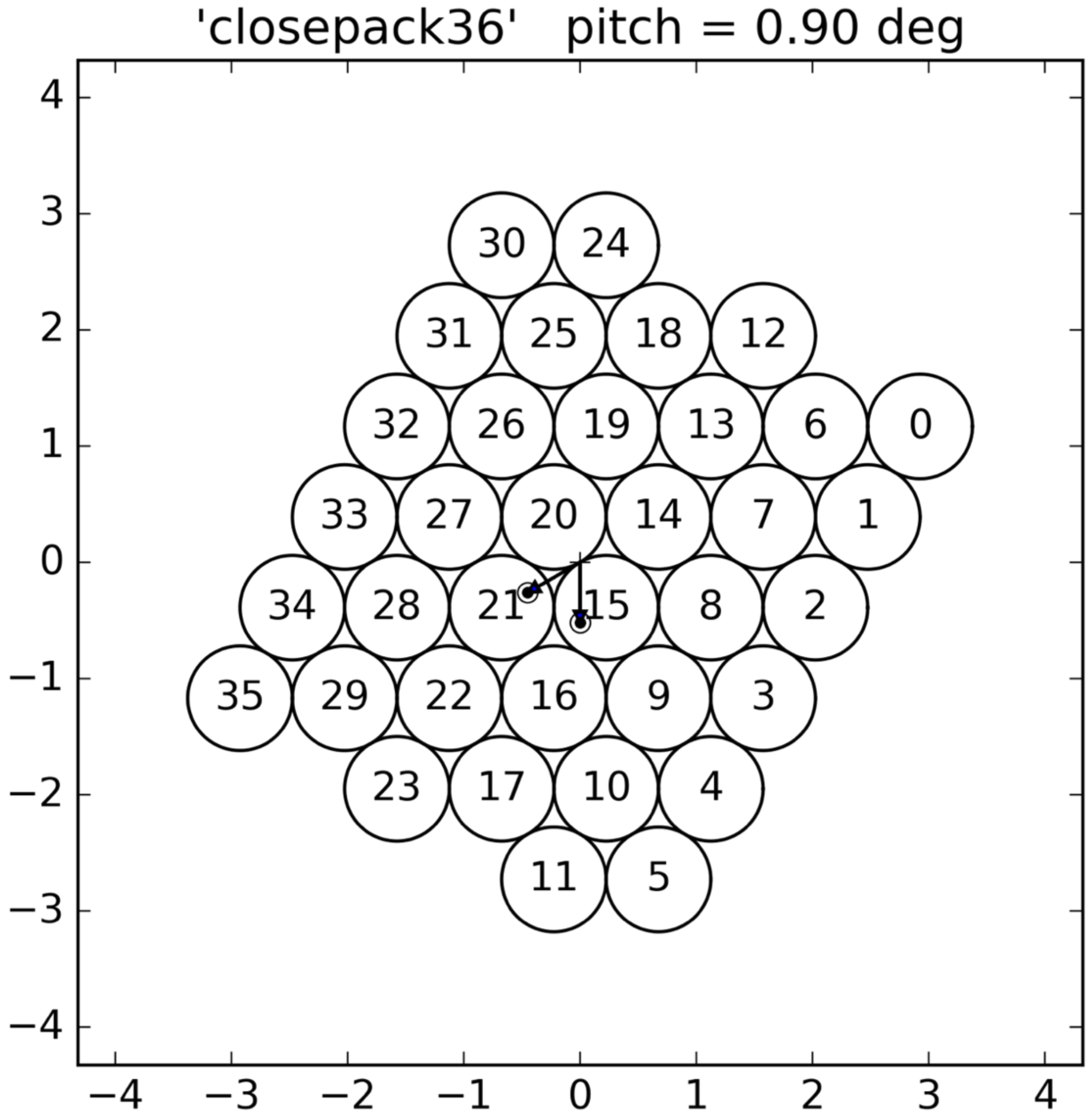




CRAFT mode/processing

- Data products produced in beamformer:
  - 1 MHz spectral resolution
  - 1.26 ms time resolution
  - Other telescopes: PKS 400 kHz/64 µs.

- Searched offline using "FREDDA" algorithm on ingest machines (mostly)/ Pawsey supercomputer (occasionally)
  - Current archive at Pawsey: 1 PB

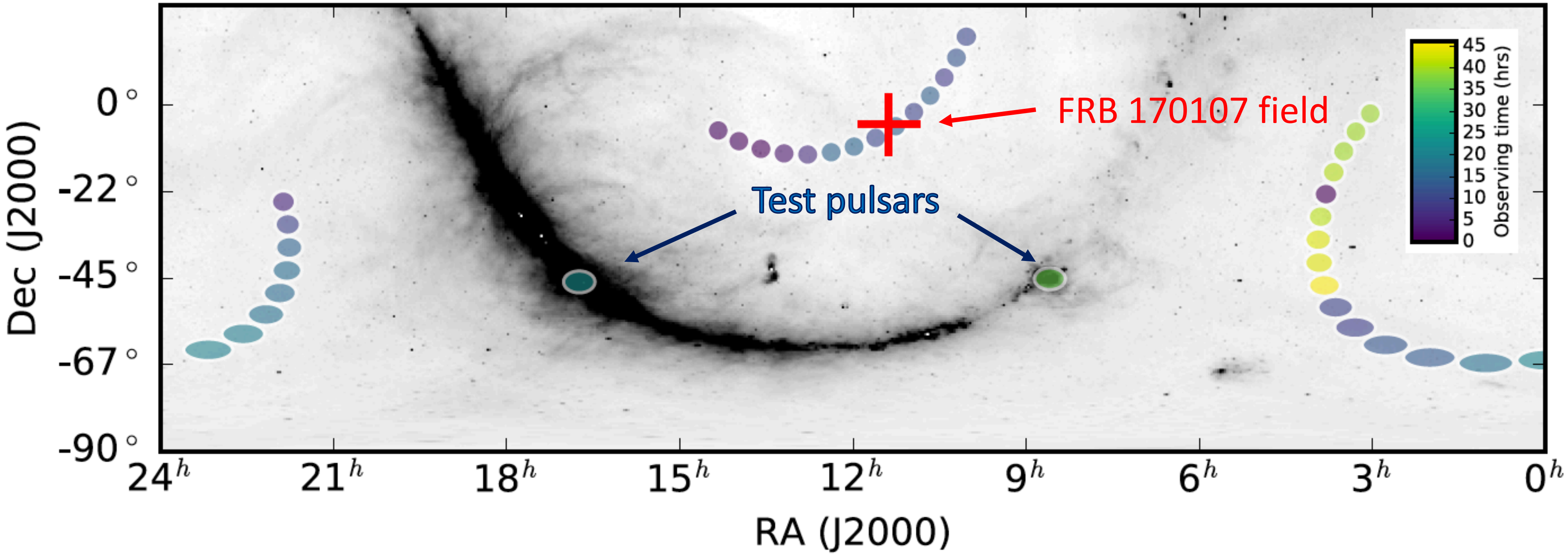


Fly's eye survey: Motivation

- ***Easy:*** **obvious first step for commissioning instrument**
- **Maximise instantaneous field-of-view**
  - Each antenna: 30 deg^2 : (currently 180-360 deg^2; in principle up to 1080 deg^2 with full ASKAP)
- **Fixed, high Galactic latitude (|*b*| = 50°)**
  - Rates higher at high latitude? (Petroff et al 2014, Macquart & Johnston 2015, but see Bhandari et al . 2018)
  - Lower DM contribution from Milky Way (30-40 pc cm^{-3})
  - 57 fields, 57 minutes per pointing: re-observe fields regularly
- **Central frequency of 1300 MHz**
  - Direct comparison to Parkes
- **Calibration:**
  - Digital beamforming done with Sun (beam weighs change from set to set)
  - For each set of beam weights, observe pulsar in all beams
  - Observe pulsar (Vela, B1641-45) at centre of a central beam (15)

ASKAP detects its first FRB

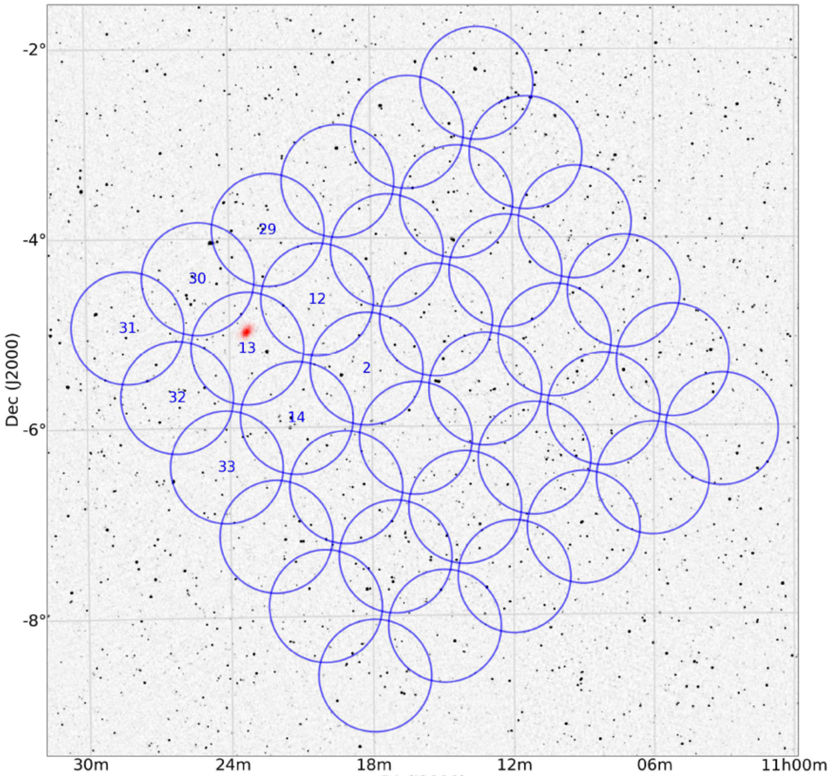
- Late 2016: new data capture modes finished
- First scientific observing run in January 2017: 6 antennas
- First FRB (170107; Bannister et al. 2017)

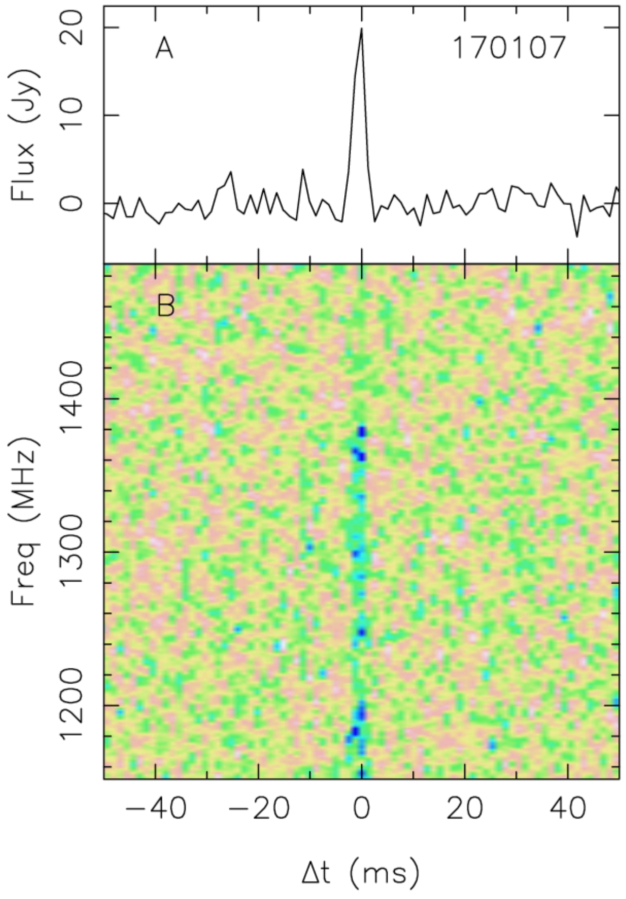


Backround: CHIpass map (Calabretta et al. 2014)

FRB 170107

- "Easy": detected FRB with 3.5 days of observing
- Dispersion measure: 609.5(5) pc cm^{-3}
- Peak flux density > 20 Jy
  - Confirms presence of population of bright FRBs
- Strong spectral cutoff





Pulse profile

Pulse spectrum after de-dispersion

Background: NVSS map of galaxies

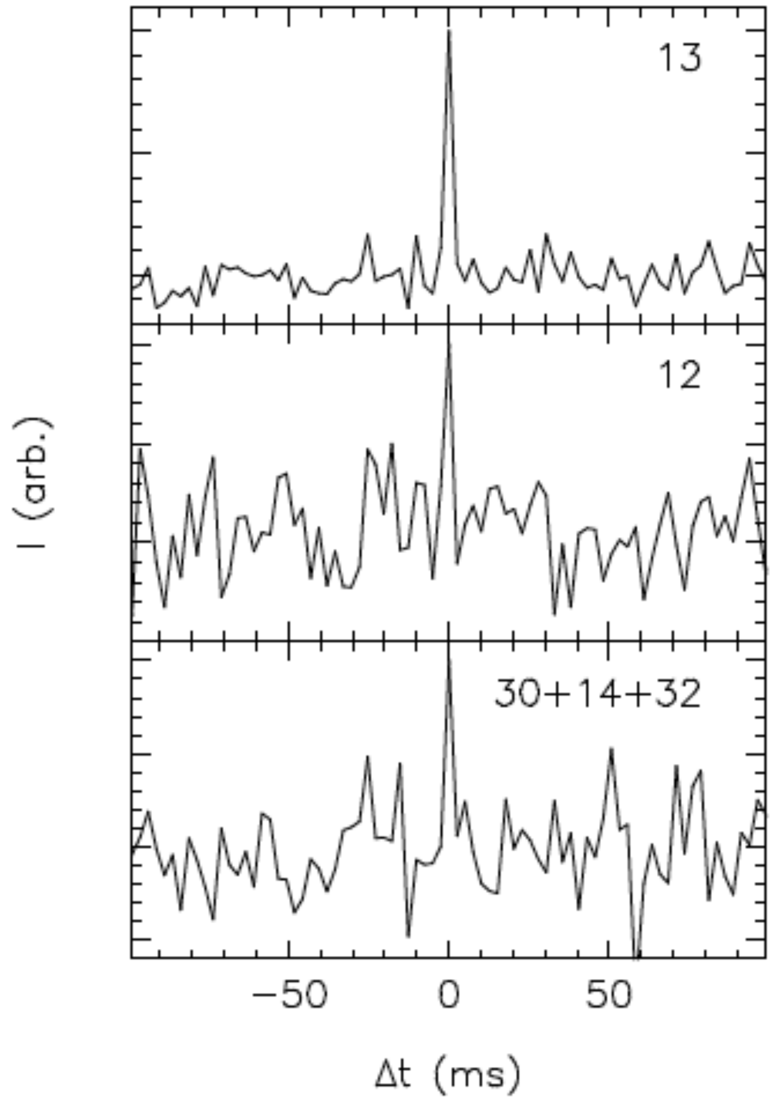
Blue: ASKAP pixels for one antenna

Red: region where FRB could be coming from

ASKAP localizations

- Overlapping beams: expect multiple detections
- Use detections (and non-detections) to determine localization of burst
  - Account for uncertainties in beam gain (sensitivity), width, and position
  - Bayesian search methods using `multinest` algorithm to sample posterior distribution
  - Achieve precision of ~ beam width/ (Signal-to-noise ratio) as expected

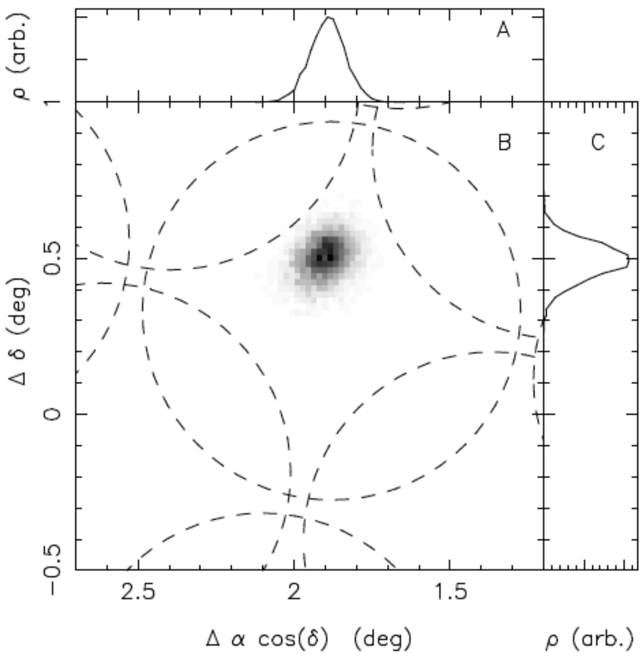
Burst profiles in different beams



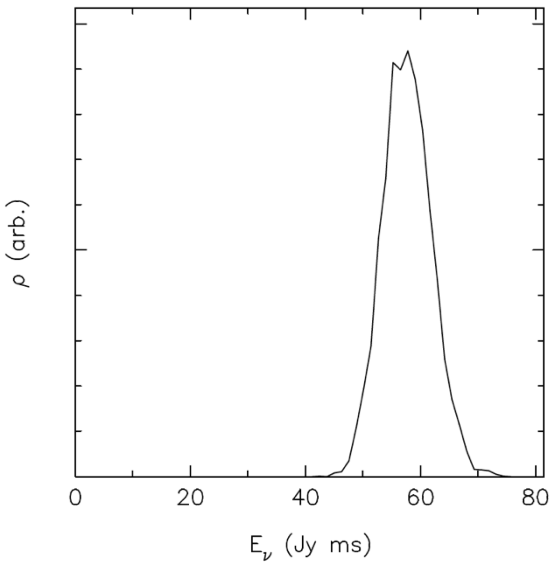
ASKAP fly's eye localizations

- Localize FRB to ~ 8x8 arcmin region (90% containment)
- Insufficient precision to identify unique host galaxy
  - Improvement over other single-dish measurements
  - Enables follow up with larger aperture facilities
- Strong constraints (upper and lower limits on burst fluence)
  - Important for constraining source brightness distribution and luminosity function
- Confirm technique by localizing pulsars to < arminute precision

Posterior localization region



Posterior energy distribution



Future of CRAFT

- ASKAP-8 ->ASKAP36
  - Remaining digital systems on site this year
  - Detection rate will depend on access to antennas but will roughly proportional to N_{ant}

- Interferometric mode commissioning
  - Real time incoherent sum searches
    - Incoherent sum detection rate is $N_{ant}^{1/4}$ worse than fly's eye
  - Trigger voltage buffers
  - Off-line correlation
  - Enables localisation + polarimetry, coherent dedispersion
- Keck/Gemini/VLT proposals for follow up/host galaxy studies