10 ans de Fast Radio Bursts (FRBs) : où en sommes-nous ?

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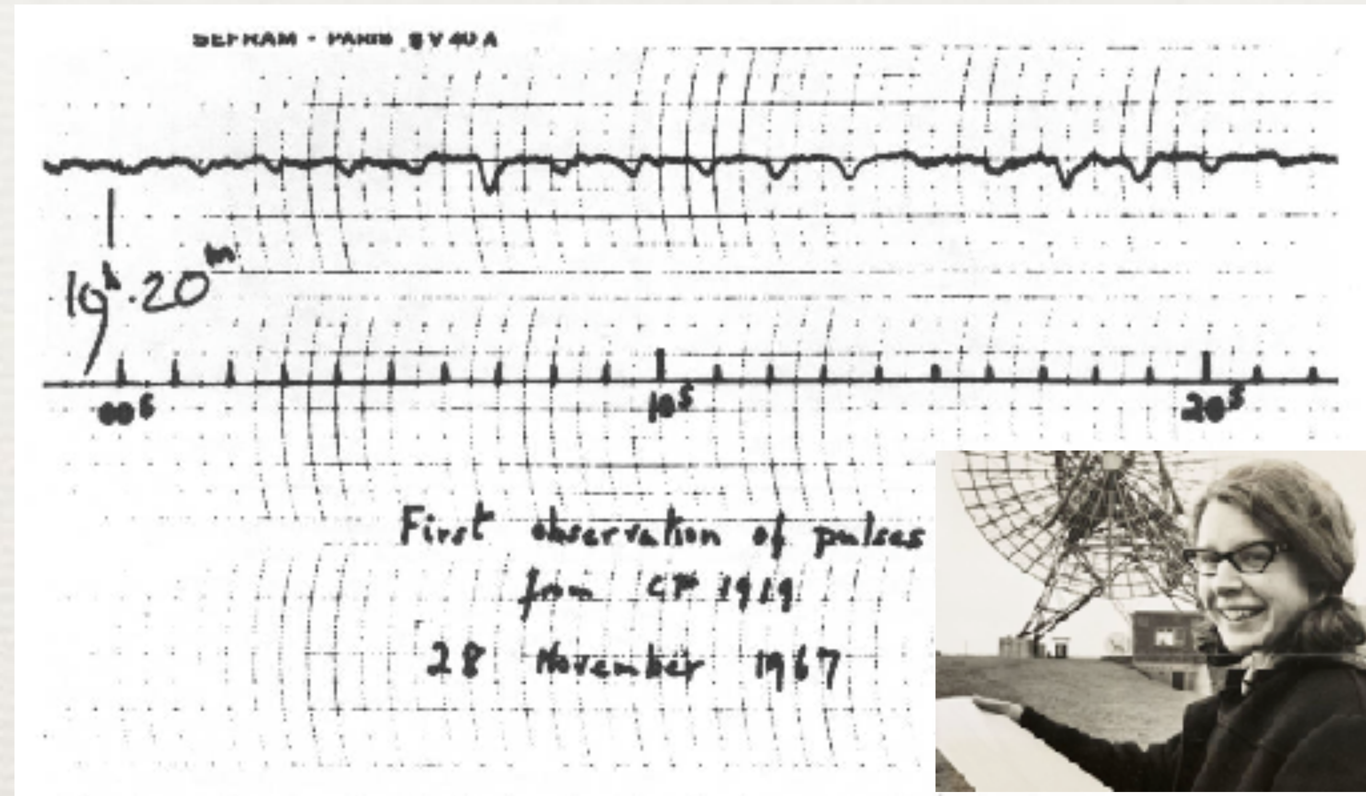
The early days of pulsar searching

1967: first pulsar discovery by Jocelyn Bell Burnell, with the Mullard radio telescope.

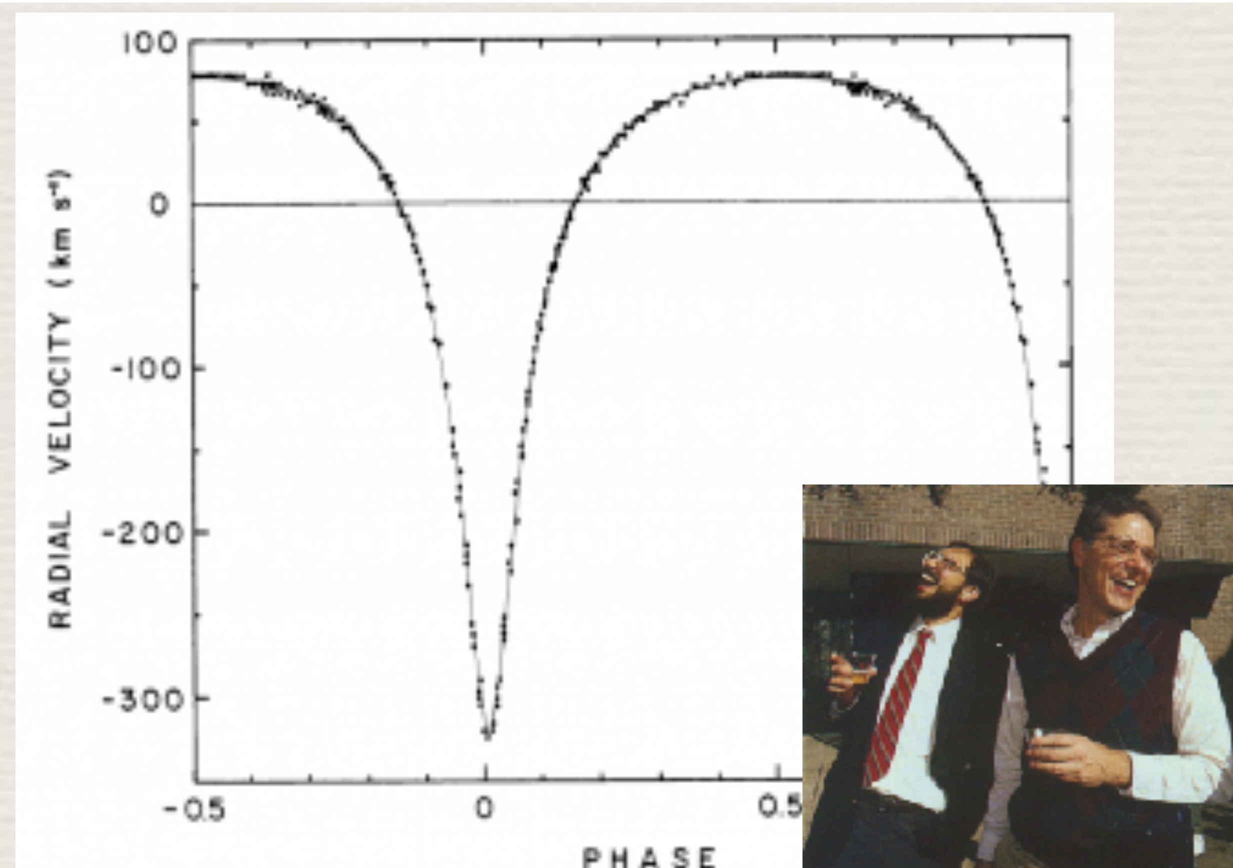
Discovery of single pulses from pulsar B1919+21, data recorded on pen charts.

Early 1970s: FFT & more powerful computers allowed larger bandwidths and integration times. No longer need to detect individual pulses!

Hulse/Taylor Arecibo survey: first to use FFTs and digital systems. Discovery of the relativistic binary pulsar B1913+16.



"I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart." (Deflections are down).



The discovery of RRATs

Early 2000s: ~2000 pulsars found by various large radio pulsar surveys. Not much single pulse searching done…

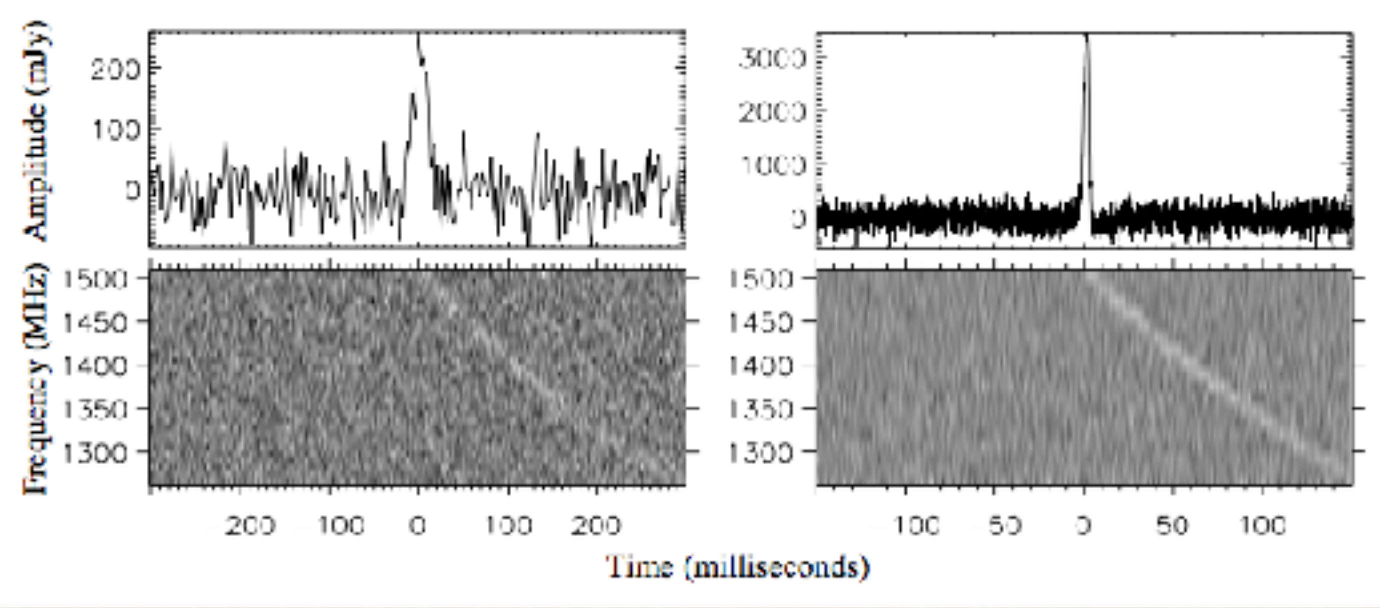
McLaughlin et al. (2006): discovery of Rotating Radio Transients (RRATs) in a dedicated single pulse search!

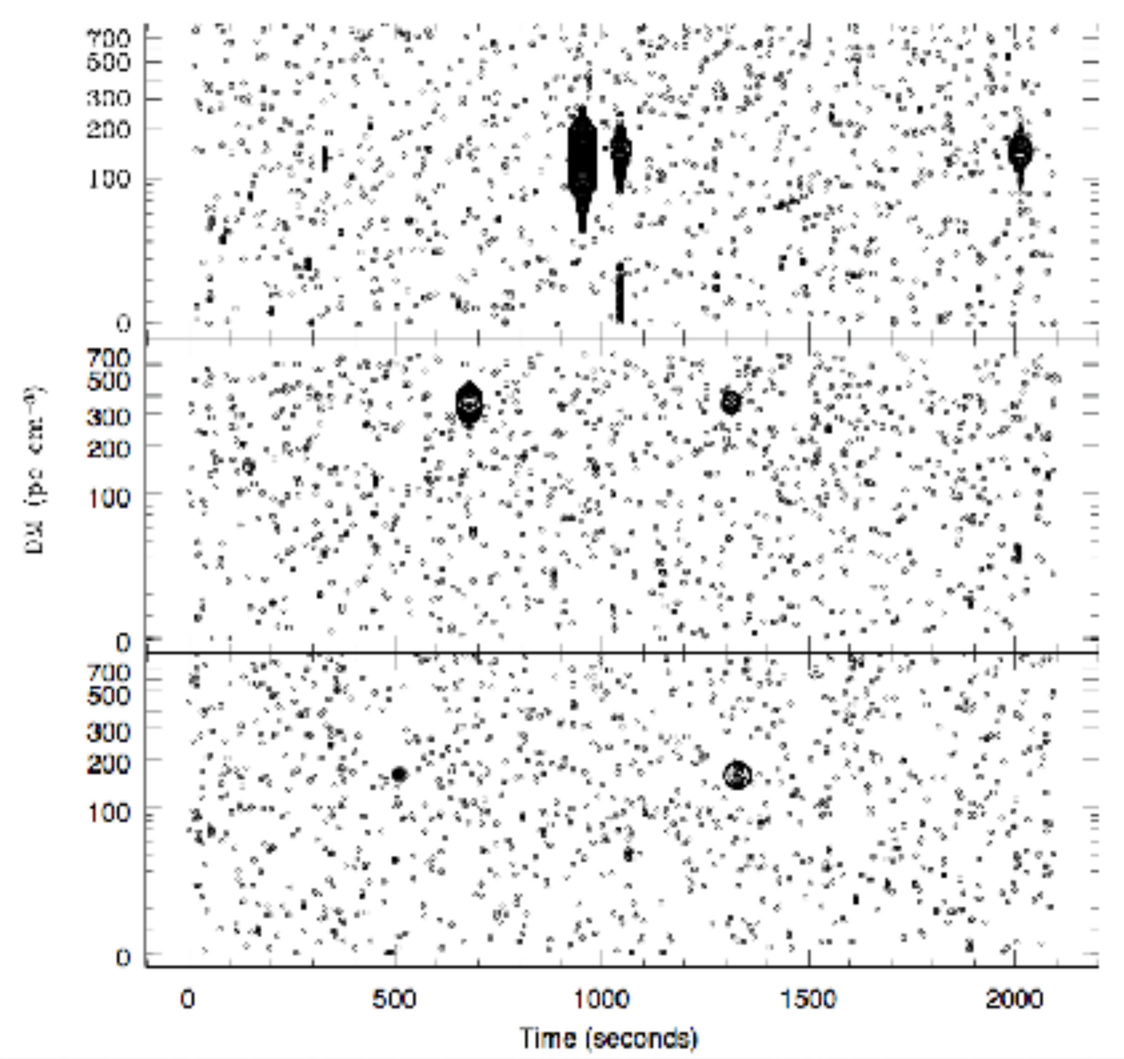
RRATs: short (few ms), sporadic but repeating (periodicity: few 0.1 to 1s) bursts of radio emission, at the same dispersion measures (DM).

$$\mathrm{DM} = \int_0^d n_e \mathrm{d}l$$

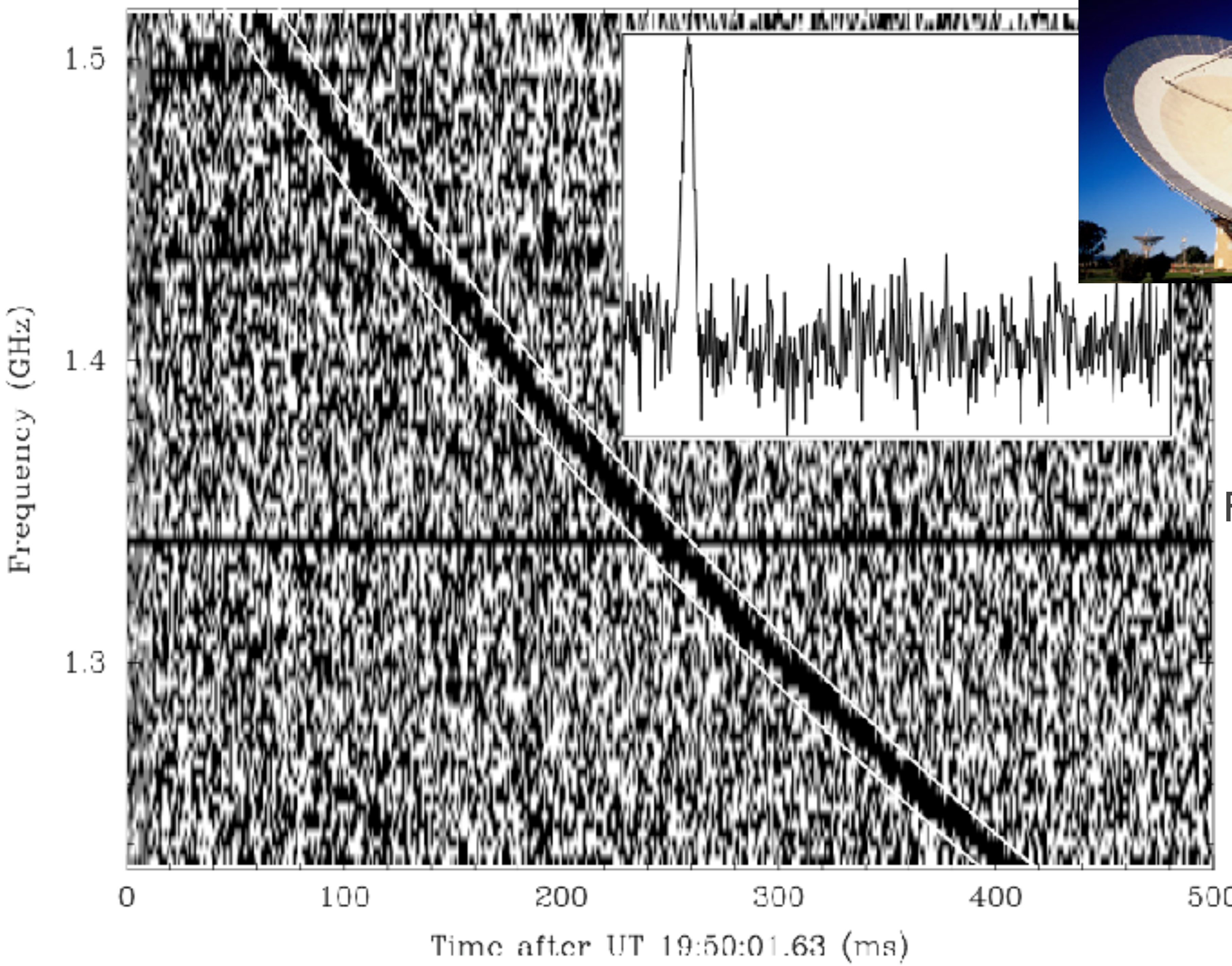
DM values suggest a Galactic origin. Most likely neutron stars.

Difficult to find with FFTs! Motivated new searches of this kind.





The « Lorimer » burst



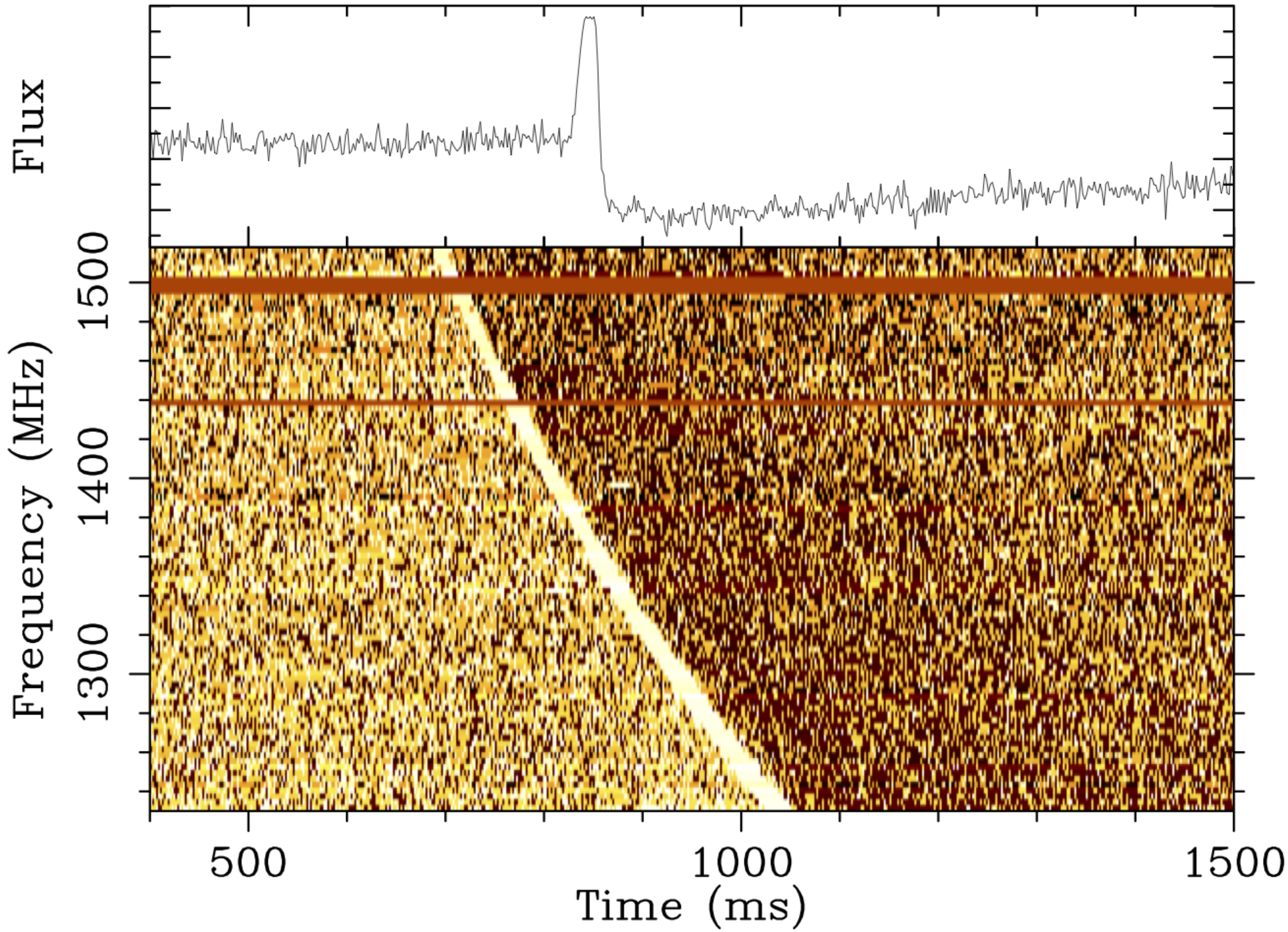
From Lorimer et al. (2007)

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

Dispersed (DM ~ 375 pc cm^{-3}), **~30-Jy, few ms** duration burst detected near the direction of the Small Magellanic Cloud, with the Parkes radio telescope!

Search motivated by the discovery of RRATs.

The « Lorimer » burst



From Petroff et al. (2019). Data were one-bit digitized and include 96 frequency channels recorded every ms. The burst was so bright that it saturated the detector!

The « Lorimer » burst (continued)

Quite a puzzling signal:

- Implied distance of ~300 Mpc!
- Extremely bright! (>10^9 brighter than RRATs)
- Does not repeat!
- Only seen at Parkes…

Also seen at Parkes (Burke-Spolaor et al. 2011): Perytons…

- Also only seen at Parkes…
- Unlike Lorimer burst, seen in all 13 beams
- Similar DMs: ~300-400 pc cm^{-3}!
- Similar durations: few ms.

… later understood to be caused by a local microwave oven (Petroff et al., 2015)!

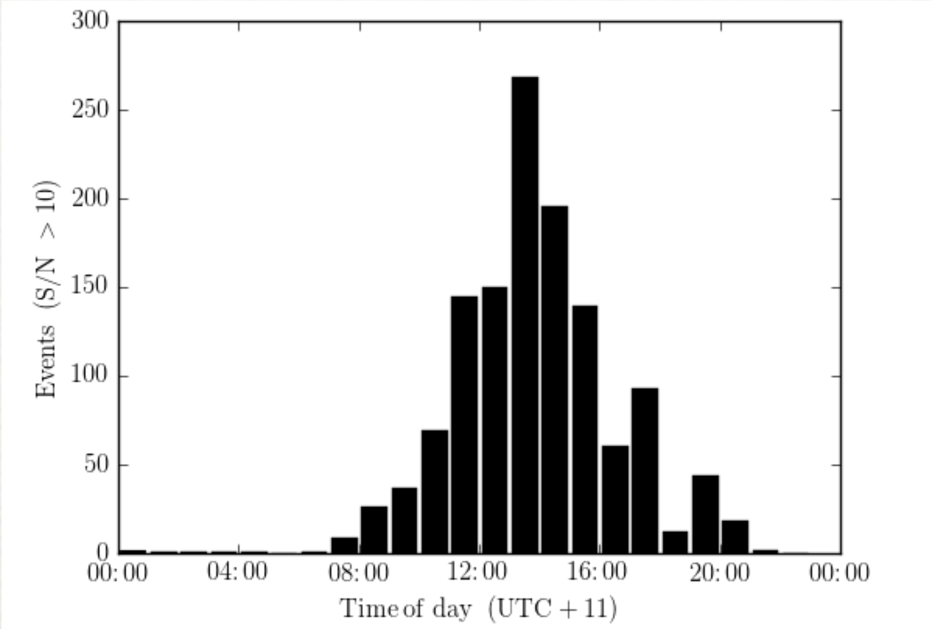


Figure 4. Number of narrow-emission spikes detected with the RFI monitor with S/N > 10 in a 60 MHz window around 2.466 GHz between 18 January and 12 March, 2015.

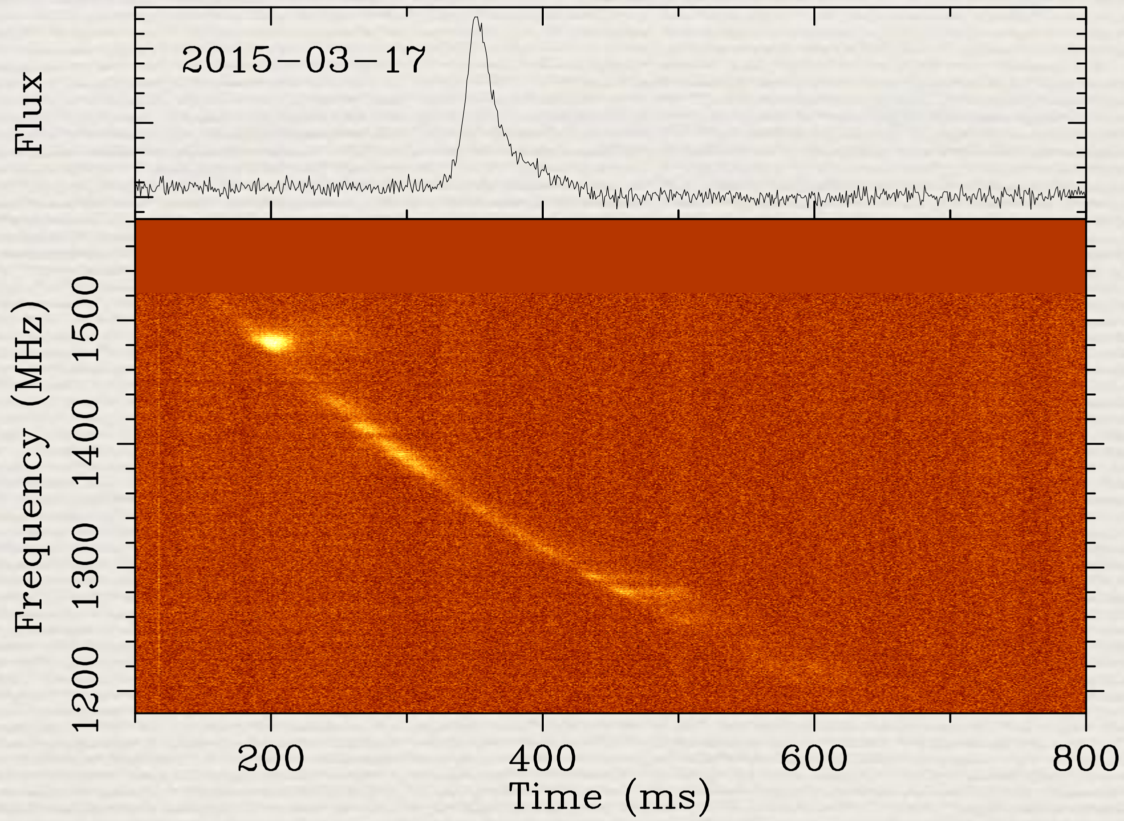
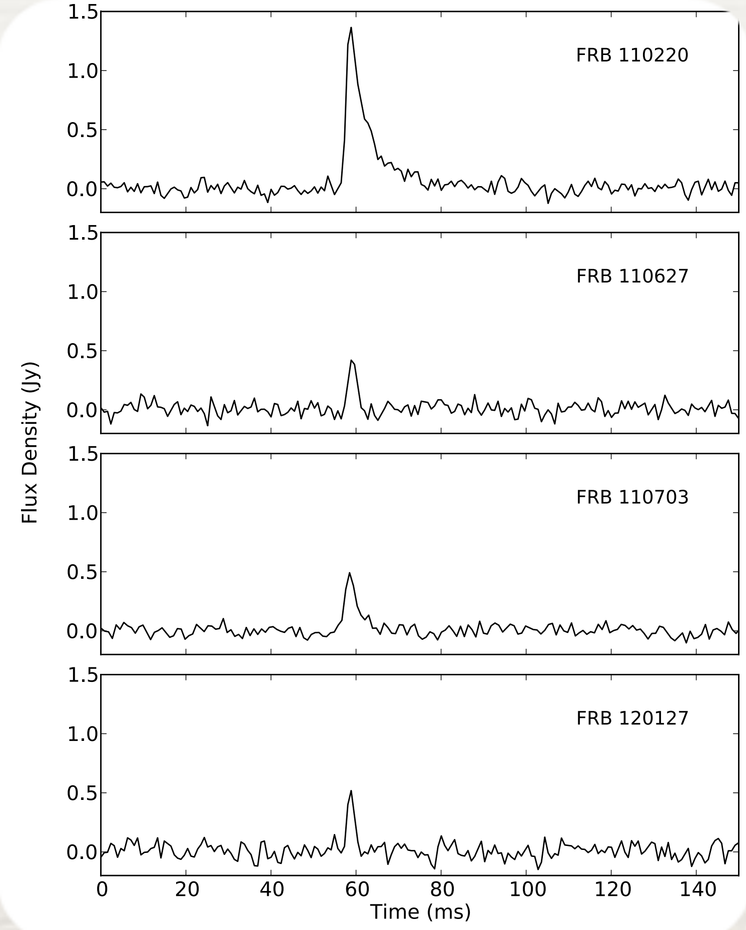


Figure 5. One of the bright perytons generated during the test on 17 March with DM = 410.3 cm^{-3} pc. RFI monitor data at the time of this peryton is shown in Figure 3.

New FRBs from the HTRU survey

Thornton et al. (2013): « a population of FRBs at cosmological distances », found in Parkes data taken as a part of HTRU.

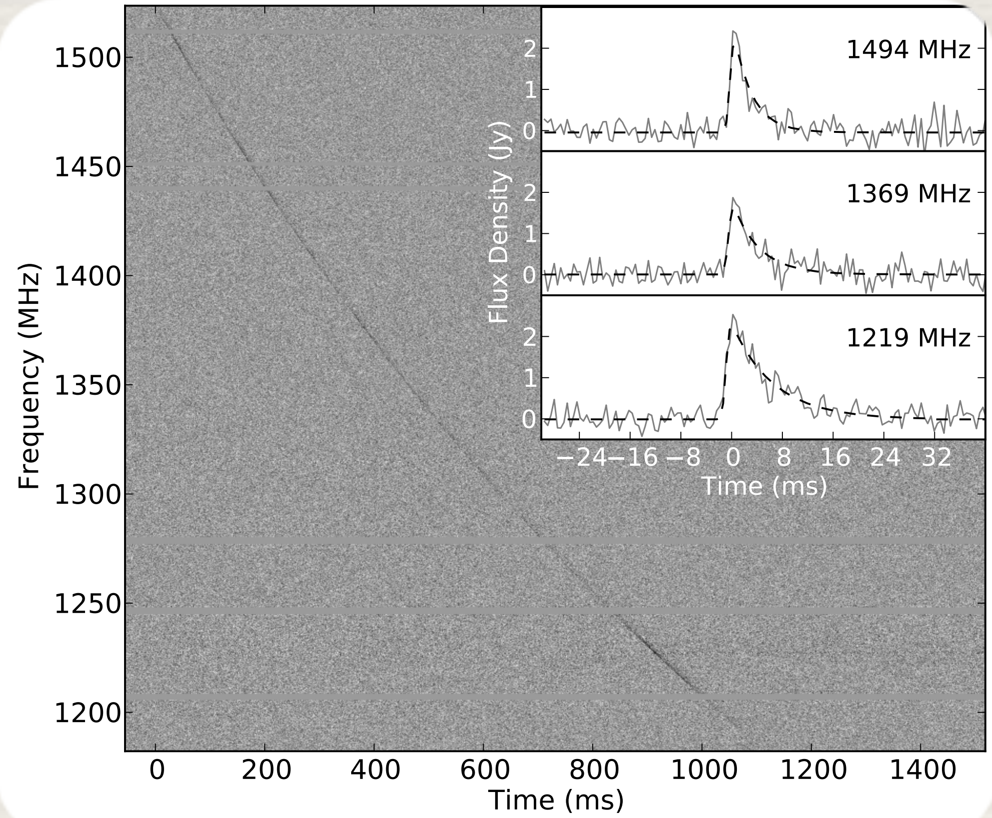
- Very high DMs (~550 to 1100 pc cm^{-3})
- few ms durations
- ~Jy peak flux density
- Unlike Perytons, dispersion & scattering (from IGM and ISM) are as expected



Implied rate: 10^4 / sky / day!

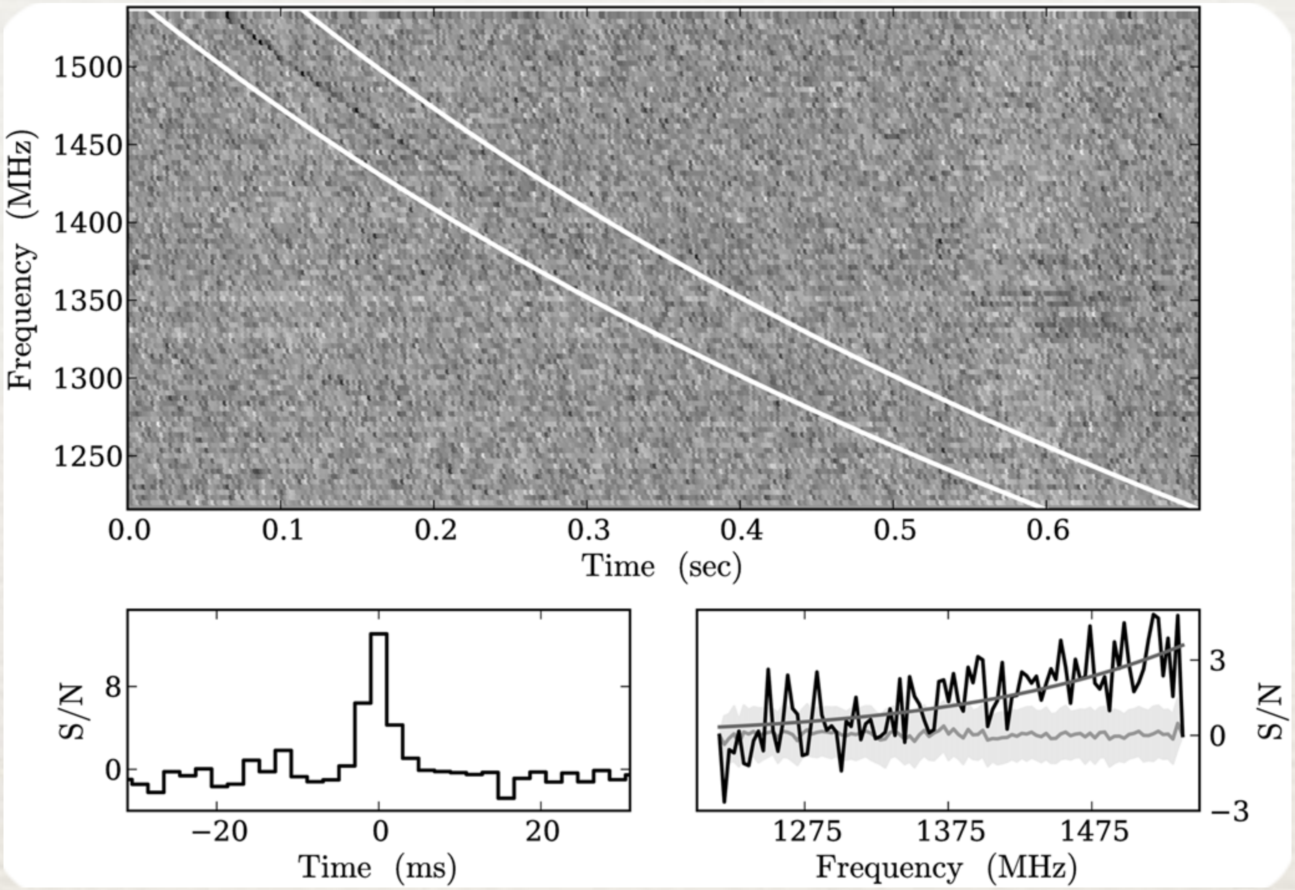
Bottom right plot: the brightest FRB of the four (FRB 110220).

Intrinsic width unresolved. Scattering tail increasing as $\nu^{-4.0+/-0.4}$!



Bursts seen from Arecibo and Green Bank

Spitler et al. (2014): detection of FRB 121105, a low Galactic-latitude (b=-0.2°, l=180°), high DM (~560 pc cm^{-3}), FRB detected with the Arecibo telescope!



First FRB not seen at Parkes.

Properties consistent with those of other FRBs (back then!).

We'll come back to this one later…

Also one (FRB 110523) seen with the Green Bank telescope in the US (Masui et al. 2015).

All previous FRBs seen at ~1.4 GHz, this one was seen at 0.8 GHz.

FRB 121105 is a repeater!

Spitler et al. (2016): re-observations of FRB 121105 with Arecibo found that **it repeats!**

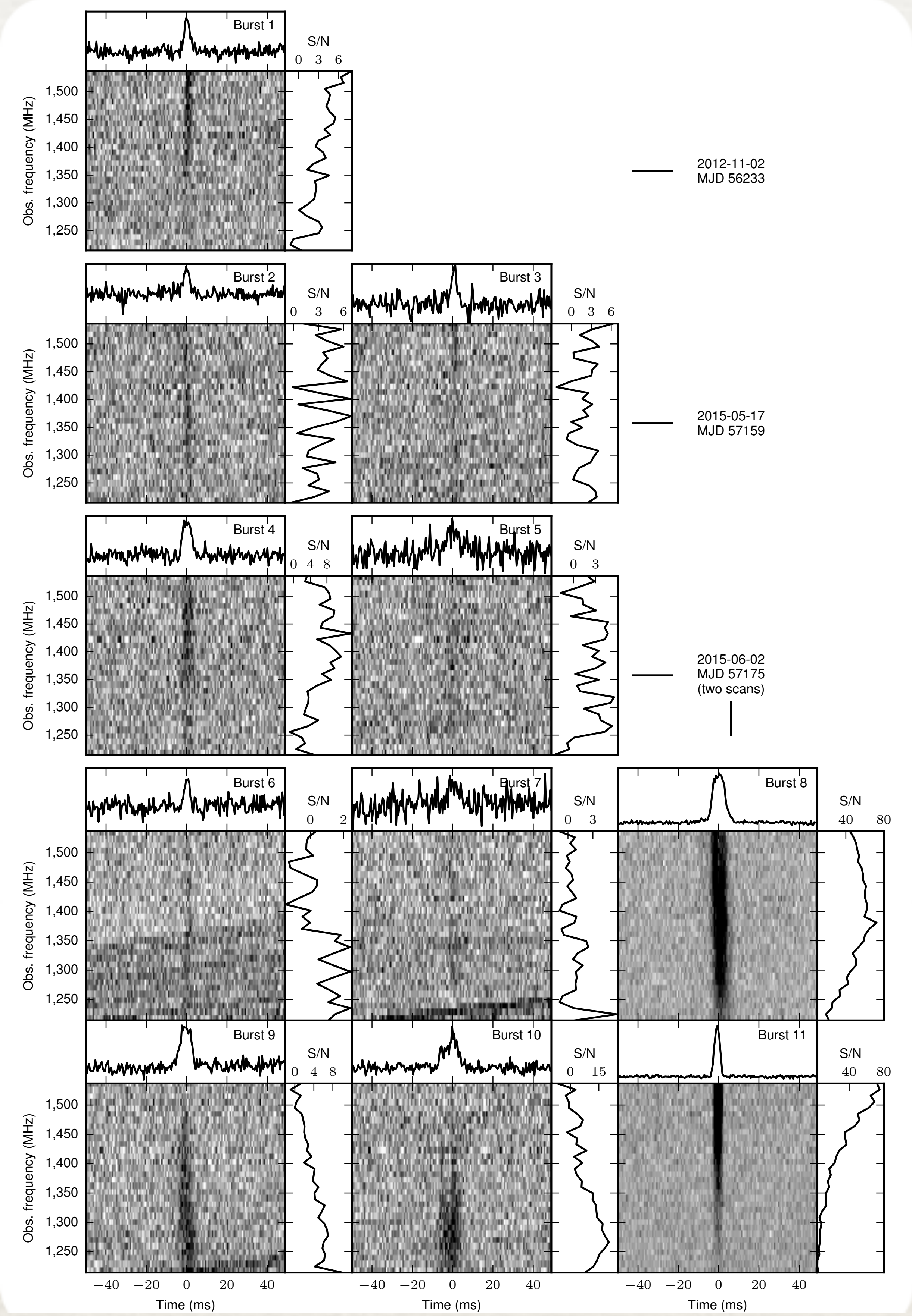
New bursts have the same DMs and sky locations as the original one.

Very active radio source: 6 bursts detected within one 10-min observation.

Hints of varying spectral properties among the detections (see plot).

Non-cataclysmic origin. Distinct FRB class?

Motivated re-observations of other FRBs for 10s to 100s of hrs. No re-detections!



FRB 121105 observations at Nançay

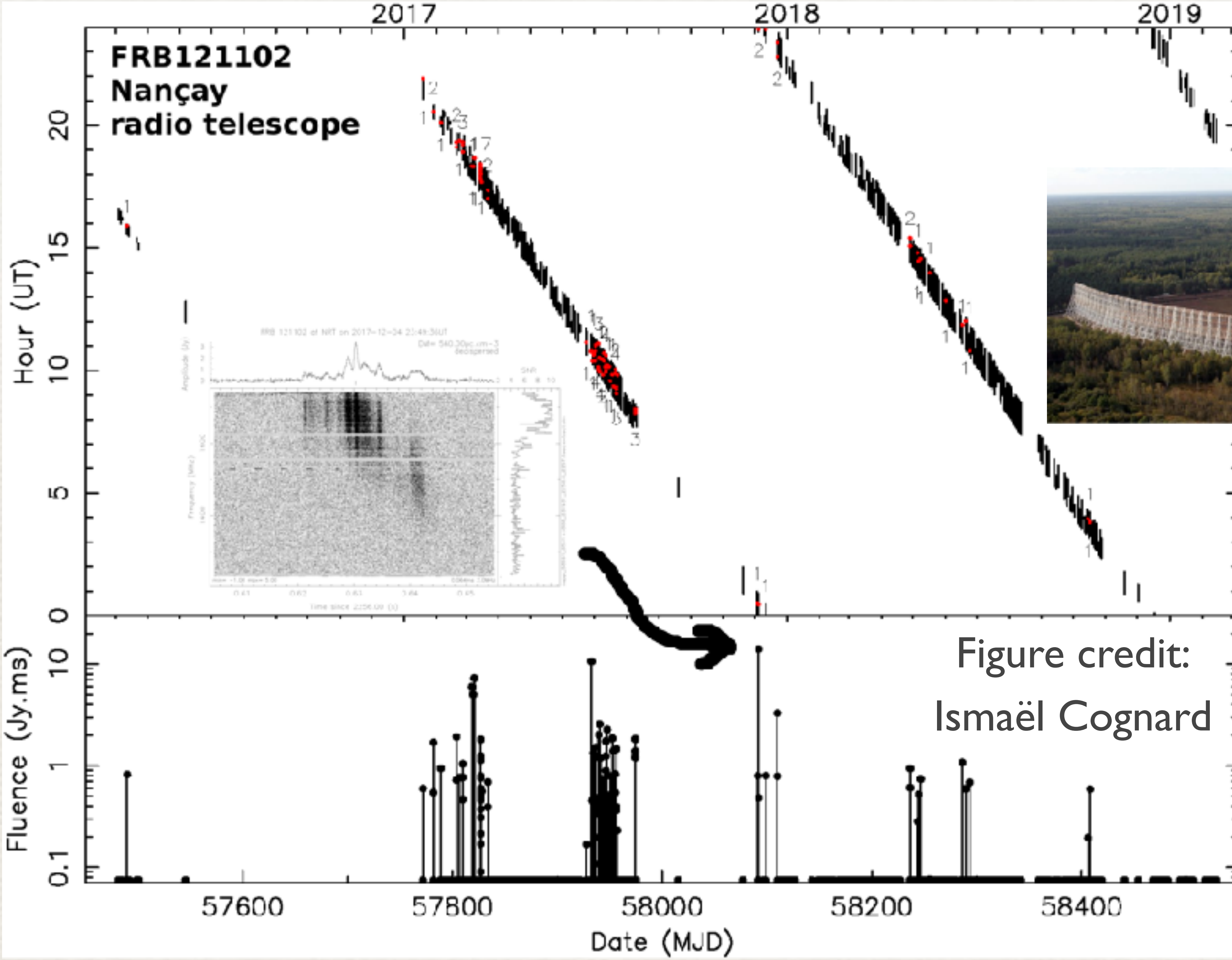
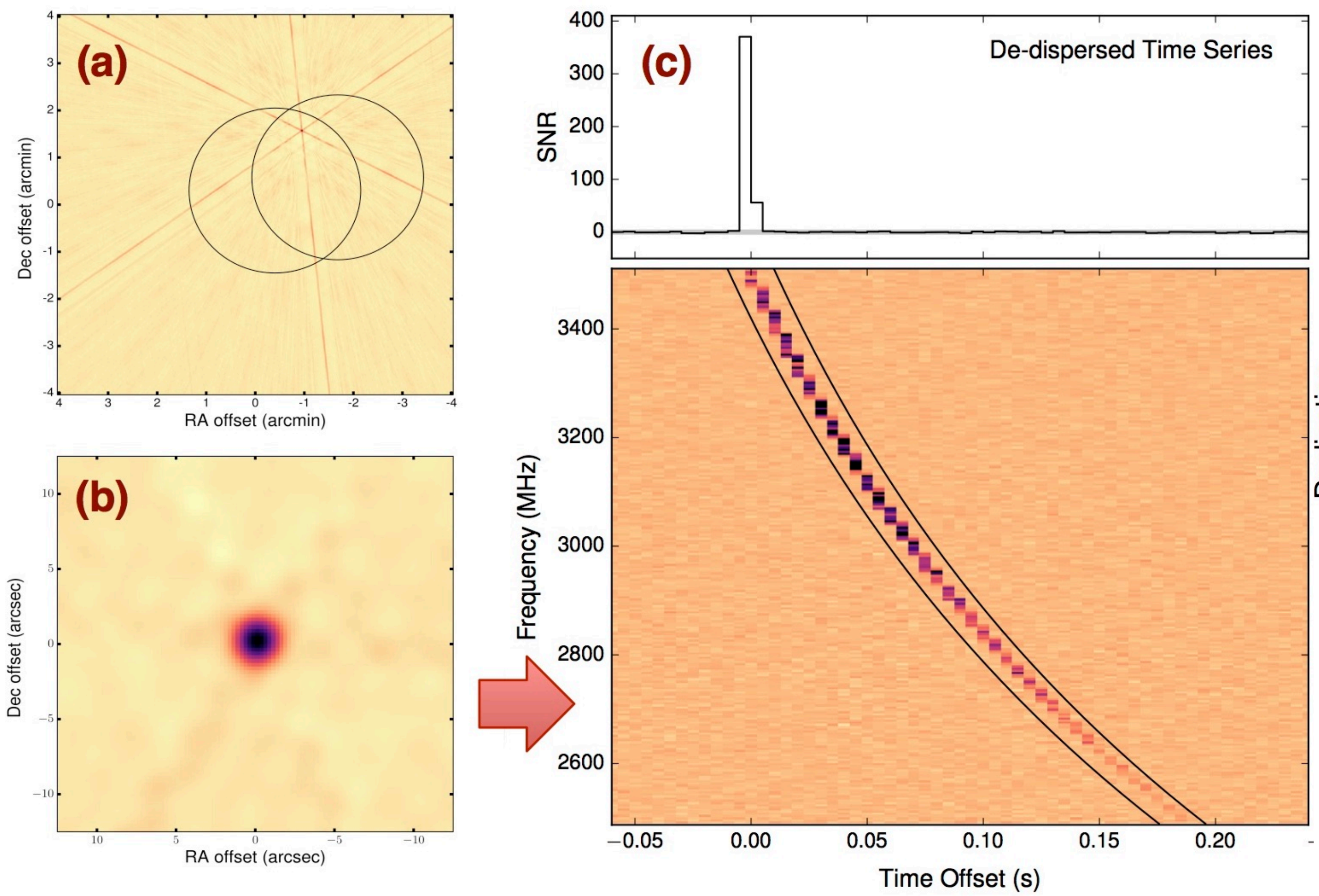
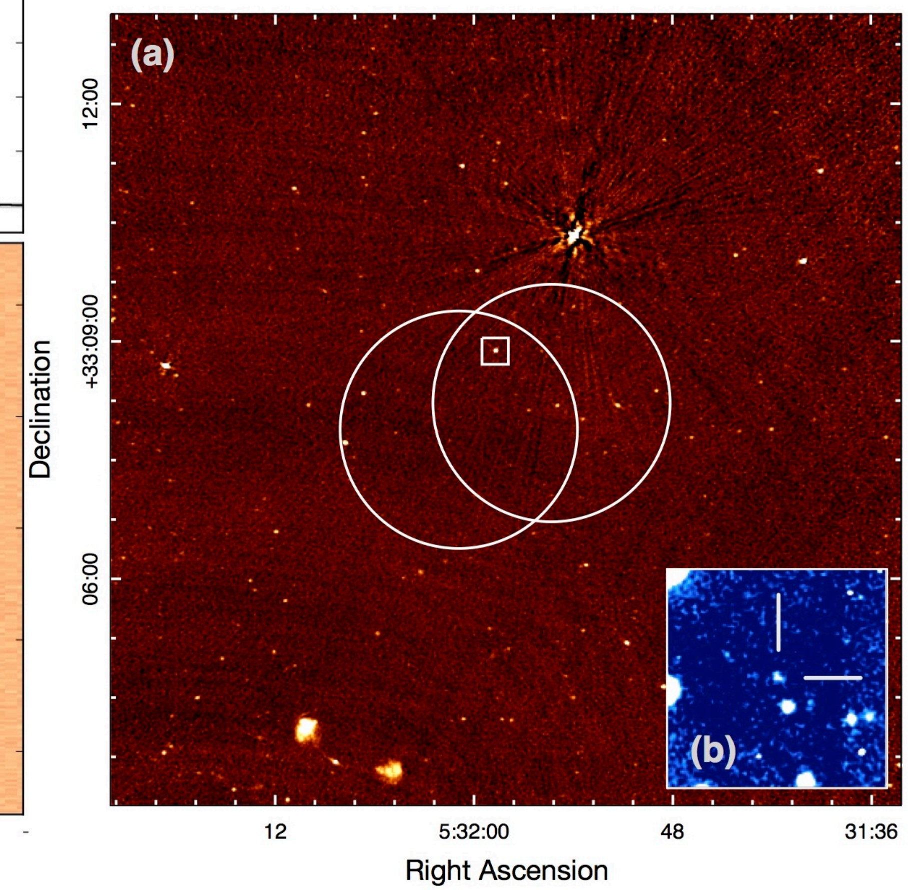


Figure credit:
Ismaël Cognard

FRB 121105 localization



(a) VLA localization of FRB 121102



(b) Host galaxy identification for FRB 121102

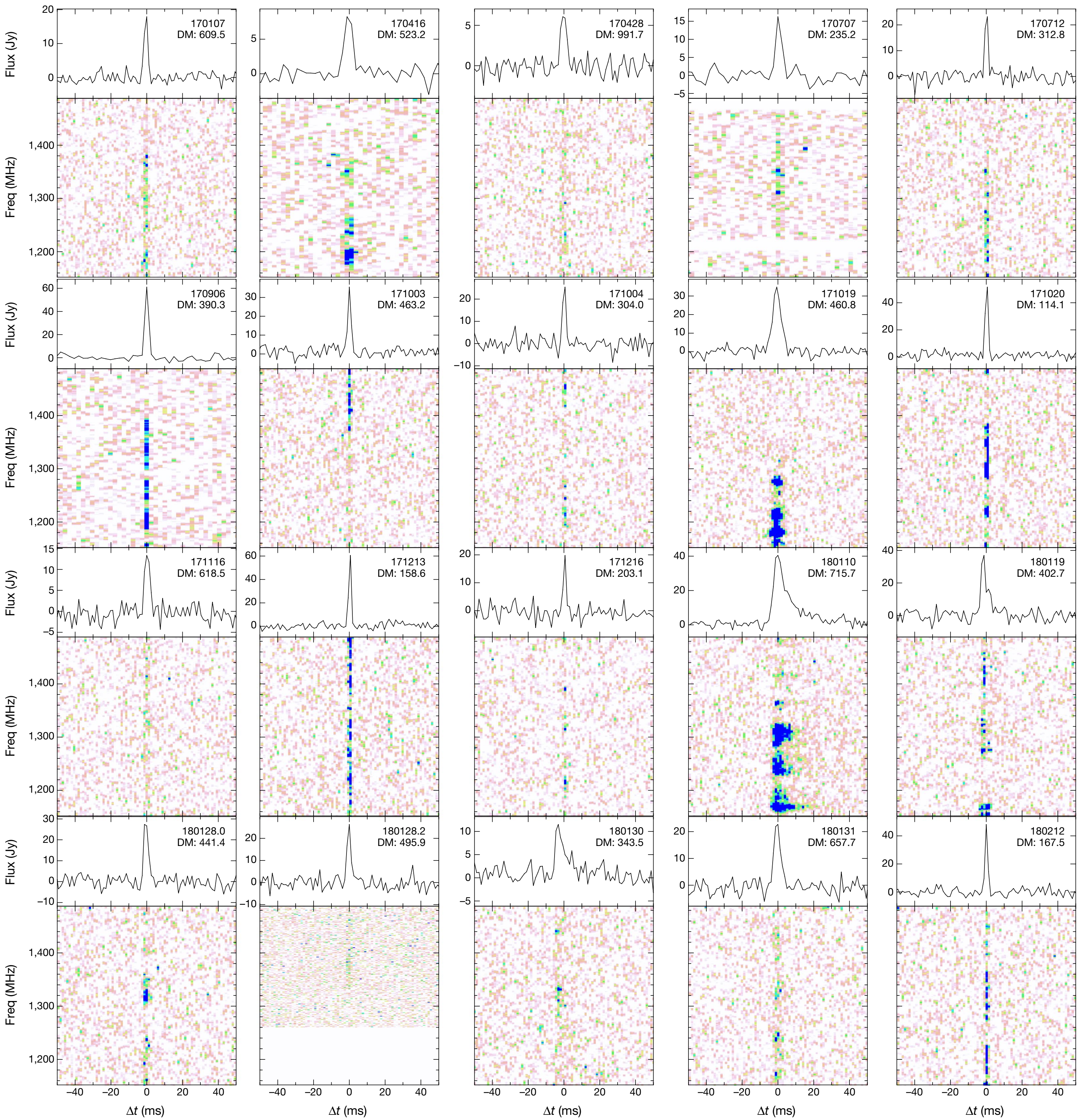
Above: VLA observation of FRB 121105 (from Chatterjee et al., 2017).

EVN obs. (Marcote et al., 2017): FRB localized to ~12 mas*, coincident with persistent radio & optical sources.

Tendulkar et al. 2017: FRB 121105 is coincident with a z~0.2, low-metallicity, low-mass dwarf galaxy. Bassa et al. 2017: position coincident with intense star-forming region.

* Typical localization for non-repeating FRBs: radio beam sizes = λ/D ~ few arcmin!

Many detections from ASKAP and CHIME



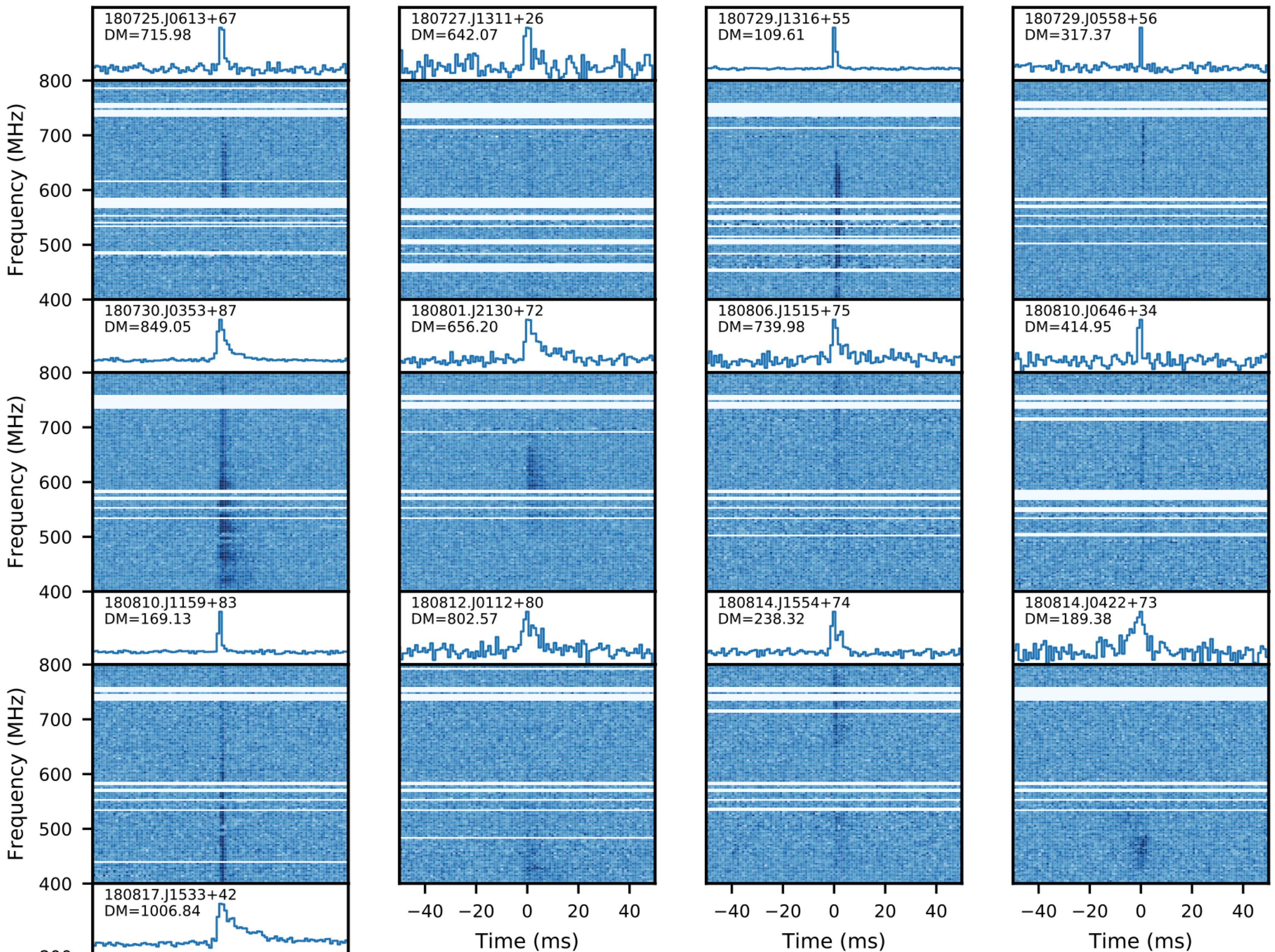
ASKAP: Australian Square Kilometre Array Pathfinder

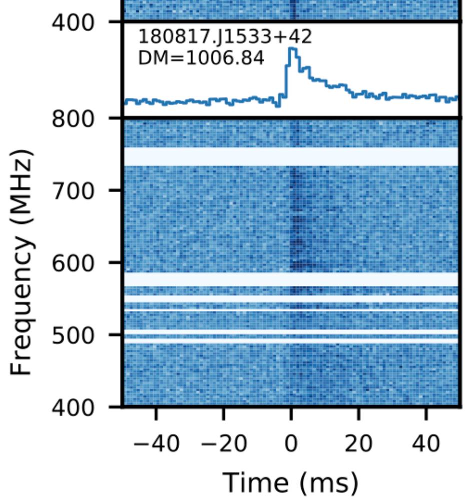
Shannon et al. (2018): 20 new FRBs found with ASKAP at 1.3 GHz.

57 pointings at |b| = 50° +/- 5°, total survey exposure of 5.1e5 deg^2 hr.

None of the 20 repeats.

Many detections from ASKAP and CHIME





CHIME: Canadian Hydrogen Intensity Mapping Experiment

Amiri et al. 2019: 13 new FRBs detected during the pre-commissioning phase.

Emission seen down to 400 MHz!
Low scattering at these frequencies.

MANY more about to be announced?

A second repeater

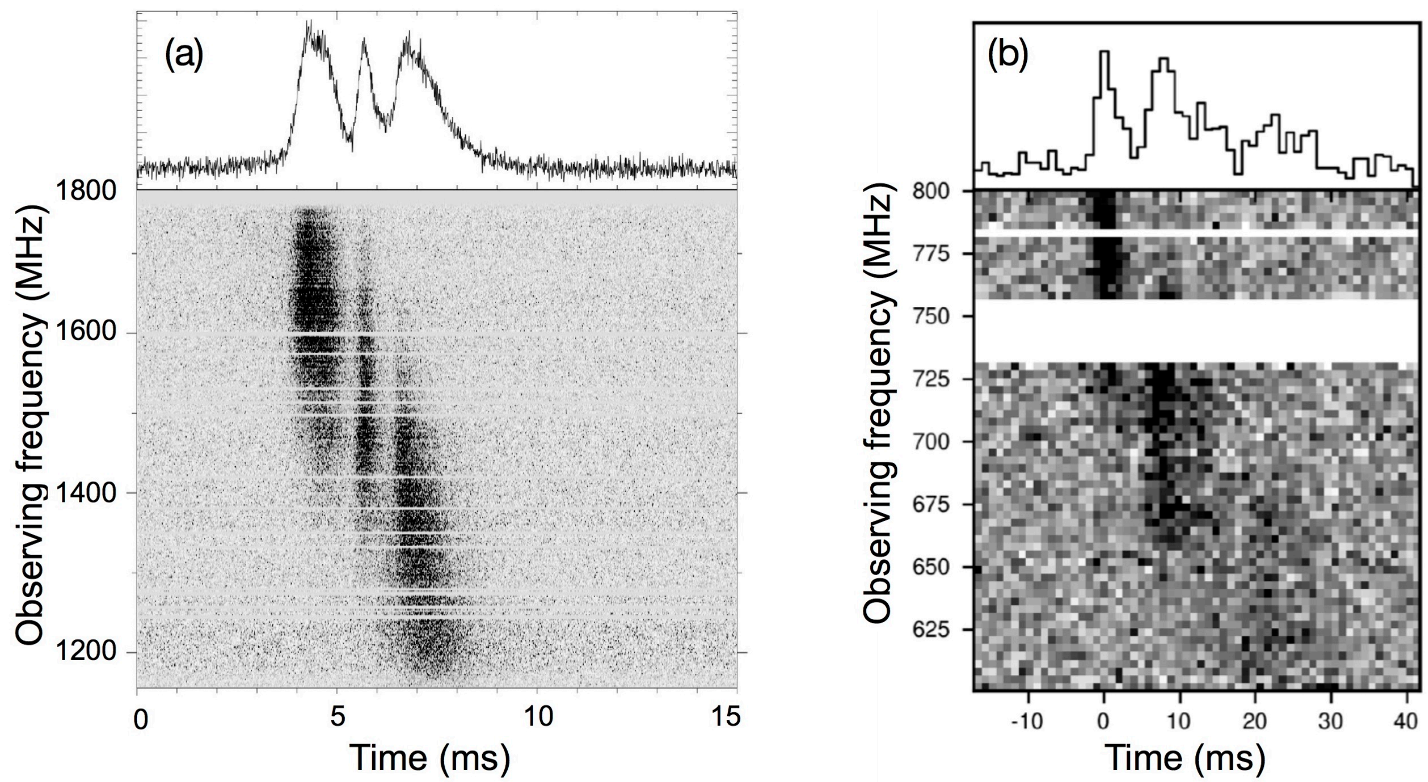


Fig. 11 De-dispersed spectra of individual bursts from (a) the repeating FRB 121102 at 1.4 GHz using Arecibo, and (b) the repeating FRB 180814.J0422+73 discovered with CHIME at 700 MHz. Both repeating sources have some bursts that show distinct sub-burst structure with descending center frequencies over time. Horizontal bands in both spectra are due to narrow-band RFI excision in the data. FRB 121102 data from Hessels *et al.* (2018). FRB 180814.J0422+73 data from CHIME/FRB Collaboration *et al.* (2019a).

Amiri et al. 2019b: discovery of a second repeating FRB by CHIME.

DM ~ 190 pc cm^{-3}, to be compared to ~560 for FRB 121105. Closer: upper limit on the redshift of z~0.1. Very similar emission features, with clear sub-burst structure in both FRBs.

Expect to discover many FRBs with wide-field instruments!

The FRB population

FRB Catalogue: http://frbcat.org/

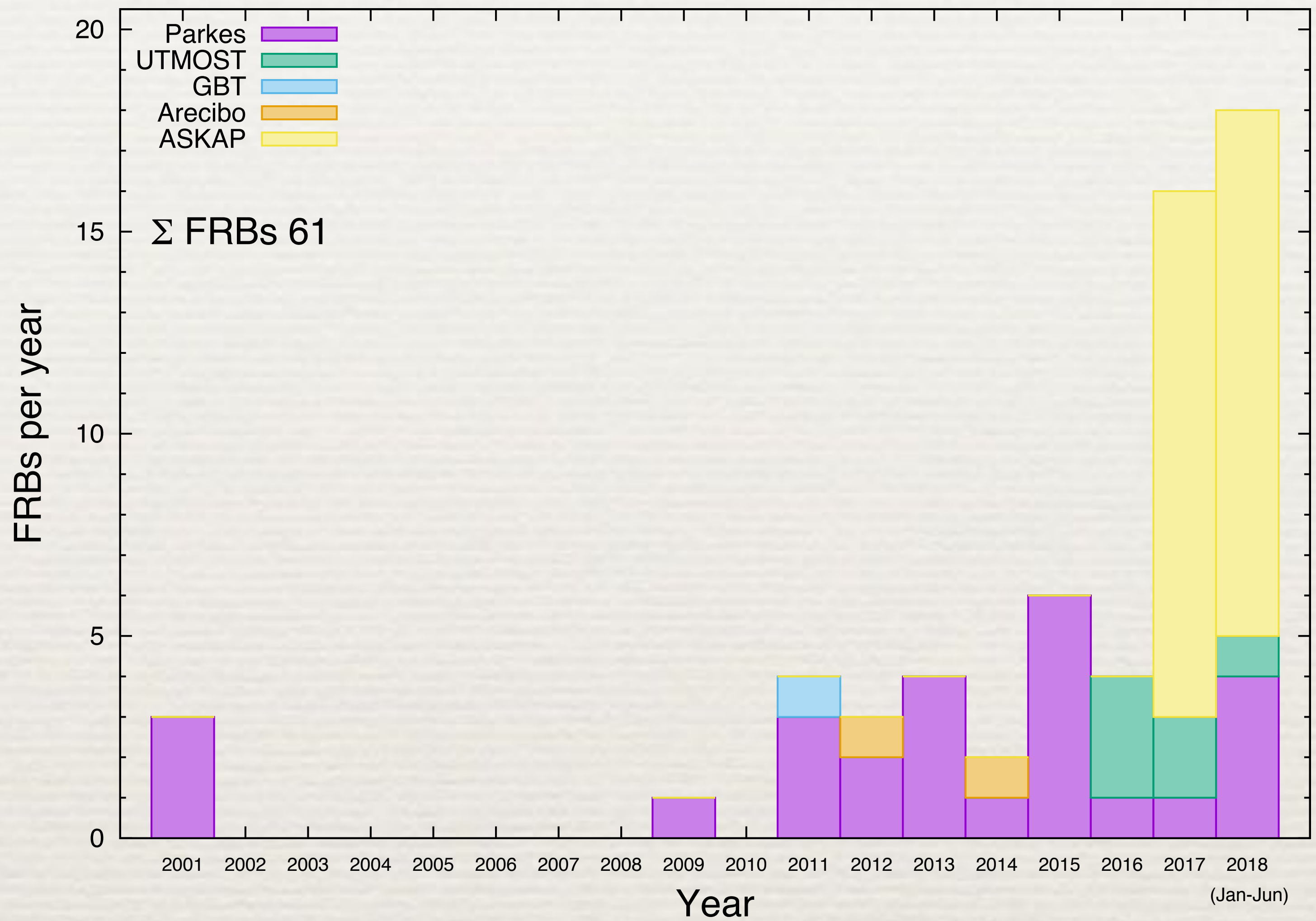
(Petroff et al., 2016)

Parkes radio telescope surveys at 1.4 GHz have provided a key contribution to the hunt for FRBs.

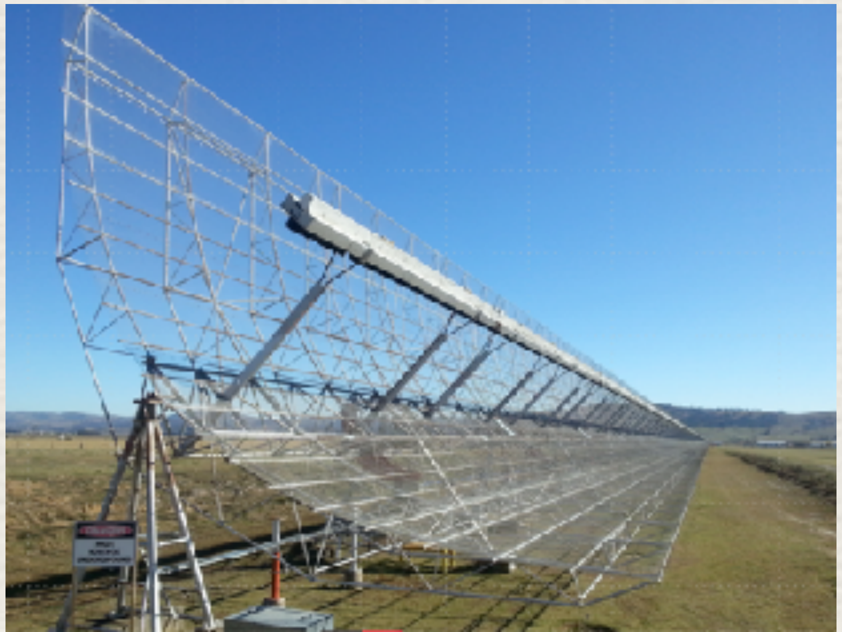
Until early 2010s, not much high-time resolution searches done…

More recently, UTMOST (Molonglo, ~800 MHz), ASKAP and CHIME have increased the FRB sample dramatically.

Note: archival data probably contains FRBs awaiting discovery…



From Keane (2019). CHIME FRBs not included.

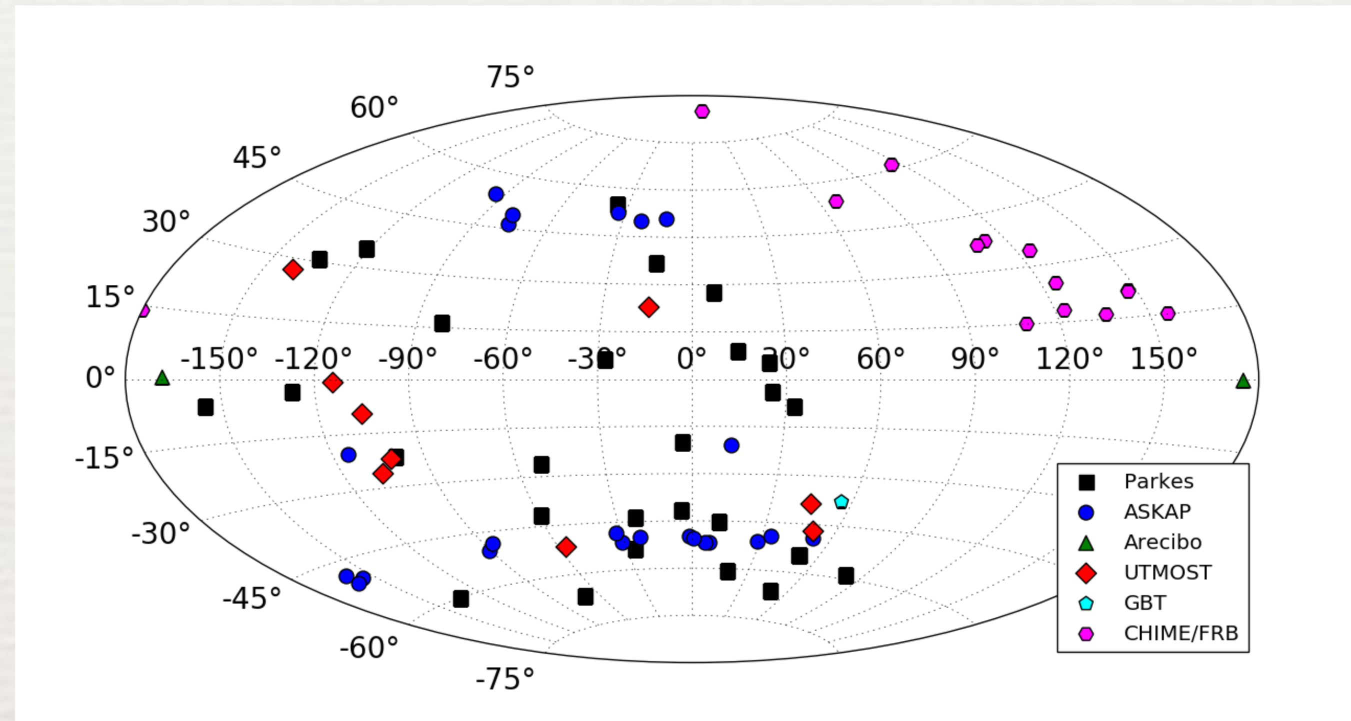


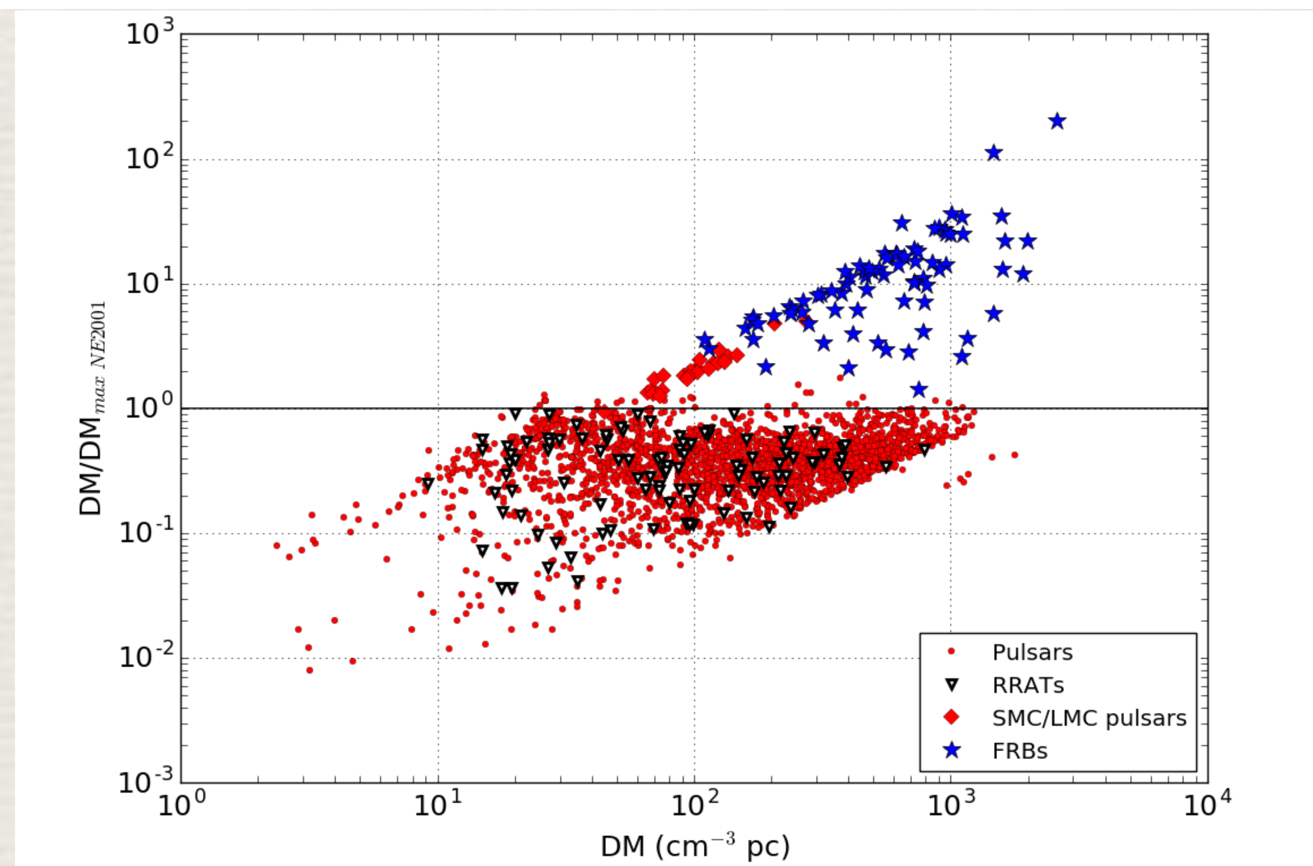
The FRB population (continued)

Top right: sky distribution, in Galactic coordinates.

Bhandari et al. (2018): no significant departure from an isotropic distribution.

Still limited by the small sample…





Bottom right: DMs of known radio pulsars, RRATs and FRBs. FRBs are extragalactic.

Minimum and maximum DM values unknown.

Current redshift range: 0.05 < z < 2.1.

Figures from Petroff et al. (2019).

FRB rates

Rate (FRBs sky^{-1} day^{-1})	Range	CI (%)	$\mathcal{F}_{\rm lim}$ (Jy ms)	Frequency (MHz)	Reference
~ 225	—	—	6.7	1400	(Lorimer *et al.*, 2007)
10000	5000 – 16000	68	3.0	1400	(Thornton *et al.*, 2013)
4400	1300 – 9600	99	4.4	1400	(Rane *et al.*, 2016)
7000	4000 – 12000	95	1.5	1400	(Champion *et al.*, 2016)
3300	1100 – 7000	99	3.8	1400	(Crawford *et al.*, 2016)
587	272 – 924	95	6.0	1400	(Lawrence *et al.*, 2017)
1700	800 – 3200	90	2.0	1400	(Bhandari *et al.*, 2018)
37	29 – 45	68	37	1400	(Shannon *et al.*, 2018)

Above: summary of various FRB rate estimates, from Petroff et al. 2019.

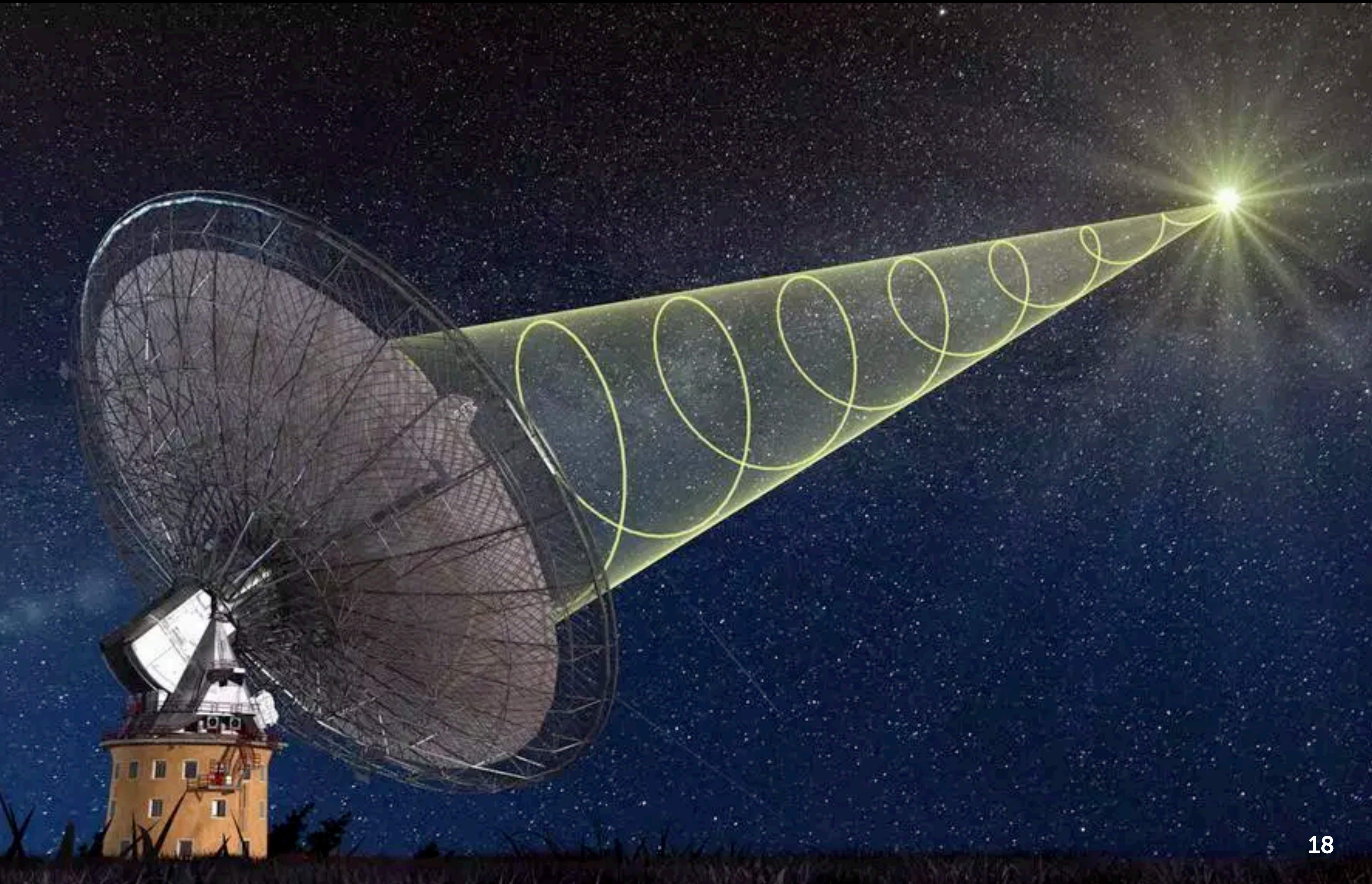
FRB redshift distribution unknown ⇒ all-sky rate estimates based on sensitivity limits.

Estimates consistent with $>10^3$ FRBs / sky / day, with fluences > 1 Jy ms.

Beaming? Volumetric rate?

Very important diagnostic for progenitor models!

So what are they?



So what are they?

Bright (50 mJy — 100 Jy) radio pulses with durations of a few ms. FRBs so far seen between 0.4 GHz to almost 10 GHz.

Bursts are highly dispersed, indicating an extragalactic origin. Current range of (implied) redshifts: $0.05 < z < 2.1$.

Until now, FRBs have only been seen in radio.

High brightness temperatures ($T_b > 10^{32}$ K) and short durations require a coherent emission process from a compact region (< 10-1000 km). Emission ~100% linearly polarized in some FRBs.

FRB progenitor(s) unknown. See next slide.

Need more FRBs, better localizations, redshift measurements, etc.!

FRB progenitor theories

The FRB Theory Wiki: https://frbtheorycat.org/index.php/Main_Page

To date, at least 55 published progenitor theories for FRBs!

Summary Table

Note: The low frequency radio range is defined to be from ~30 MHz to 3 GHz and the high frequency radio range is defined to be from 3 to 30 GHz.
The table is too wide to fit on all screens — Scroll right to see other columns.

Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X ray Counterpart	Gamma ray Counterpart	GW Counterpart	Neutrino Counterpart	References	Comments
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	Yes	--	--	--	--	Yes, but unlikely detectable	--	--	URL	None
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH.
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH. GW from collapse and persistent GWs from SS.
Jet-Cavitron	AGN	Jet-Cavitron Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	Yes	--	URL - URL	Persistent scintillating radio emission.

FRB progenitor theories (continued)

See FRB Theory Wiki. Majority of models: neutron stars (large rotational energies, strong B fields, etc.).

- Isolated NS models: supergiant pulses from NSs (i.e. Crab-like)? Magnetically-powered NSs with ultra-strong B fields? Supermassive NSs collapsing into black holes?

- Interacting NSs: plasma hitting the magnetosphere of a NS? Rocky bodies impacting NSs? Colliding neutron stars?

- Black hole progenitors: collisions of clumps in BH jets? Binary BH mergers, with one BH carrying charge? BH-NS mergers?

- White dwarf progenitors: accretion-induced collapse of a WD?

- Other? Superconducting cosmic strings? Beamed emission powering sails of distant spacecraft?

One or more types? What about repeaters? Need more FRBs of all types!

FRBs as probes of cosmology

FRBs are bright radio transients at cosmological distances!

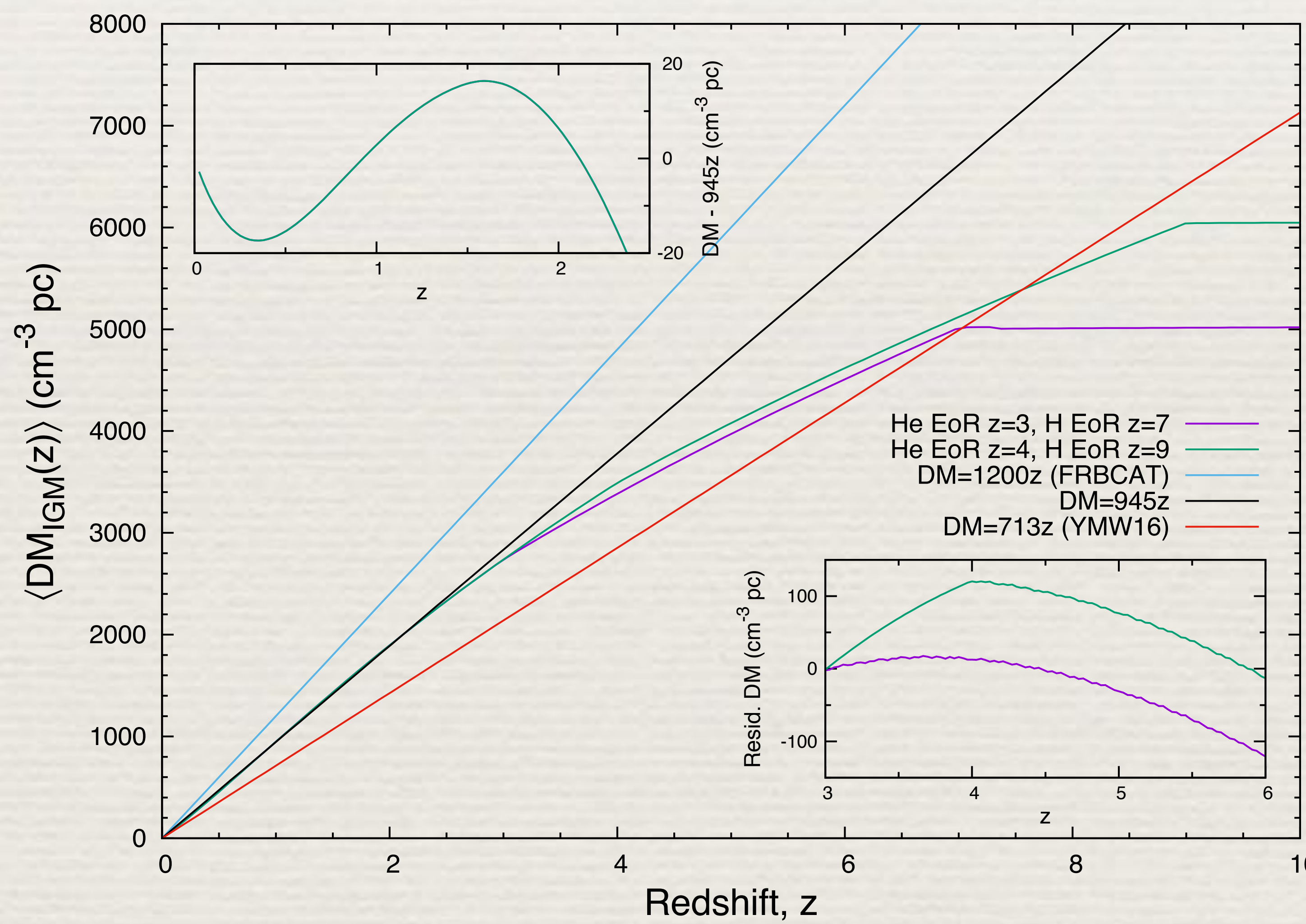
- DM-z relation: « cosmic ruler »
- Probes of the IGM (primordial B field? IGM density?)
- Where are the missing baryons?

$$\langle \mathrm{DM}(z) \rangle = \int_0^z \frac{f_{\mathrm{IGM}}(z')(1+z')\left(\frac{3}{4}X_{\mathrm{H}}(z') + \frac{1}{8}X_{\mathrm{He}}(z')\right) dz'}{\left(\Omega_{\mathrm{m}}(1+z')^3 + \Omega_{\mathrm{k}}(1+z')^2 + \Omega_\Lambda \exp\left(3\int_0^{z'} \frac{(1+\omega(z''))dz''}{1+z''}\right)\right)^{1/2}}$$

Average DM as a function of redshift <DM(z)> depends on several cosmological parameters:

- energy density of matter Ω_m, baryons Ω_b, dark energy Ω_Λ, curvature Ω_k
- ionization fraction of the IGM, $f_{IGM}(z)$
- dark energy EoS parameter $\omega(z)$
- reionization histories for H, $X_H(z)$, and He, $X_{He}(z)$

Need MANY MORE DM & robust z measurements!



From Keane (2019). Average DM due to the IGM as a function of redshift, under various scenarios.

Summary and prospects

FRB science is evolving extremely rapidly!

Yet, a lot is still to be learned about FRBs.

Not much talked about today:

- emission properties (spectra, etc.)
- polarization properties (linear/circular pol., rotation measures…)
- From DMs to redshifts…

Fantastic FRB detectors coming online: ASKAP, CHIME, APERTIF, MeerKAT, SKA…

Expect 100s of FRB discoveries in coming years!

Counterparts at higher energies? Low-frequency observations (LOFAR, NenuFAR, etc.)?

Stay tuned for new FRB discoveries!