Fast Radio Burts

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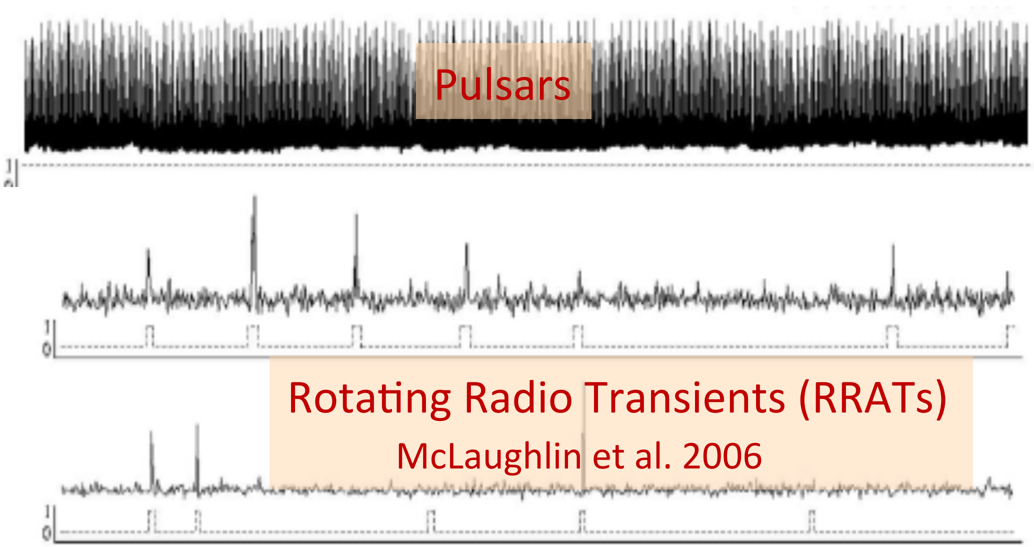
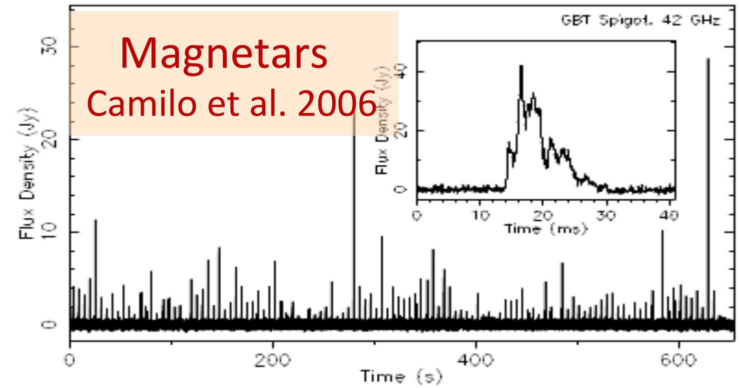
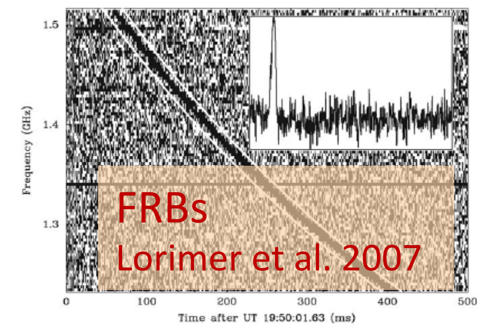
Outline

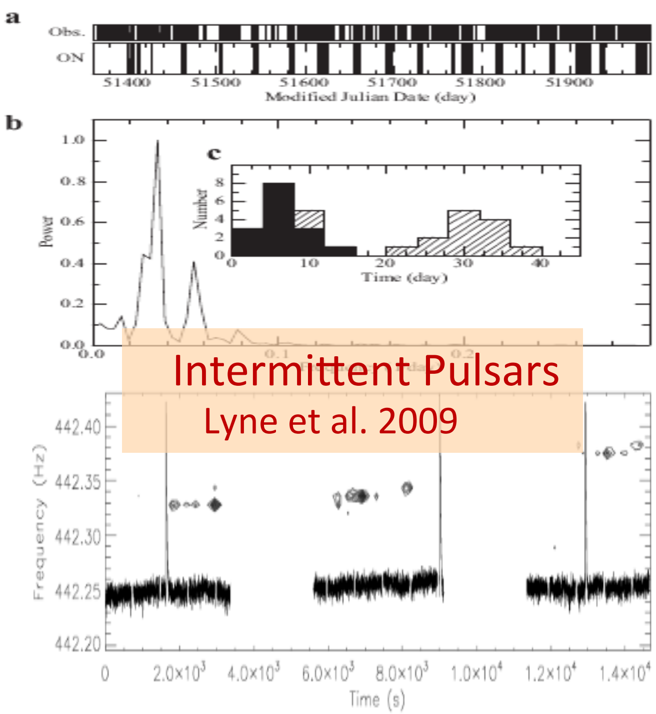
- Time-domain universe
- Fast Radio Bursts (FRBs)
- Searching for FRBs (probing extreme cataclysmic events)
- Searching for Pulsars and FRBs with the GMRT: GHRSS survey

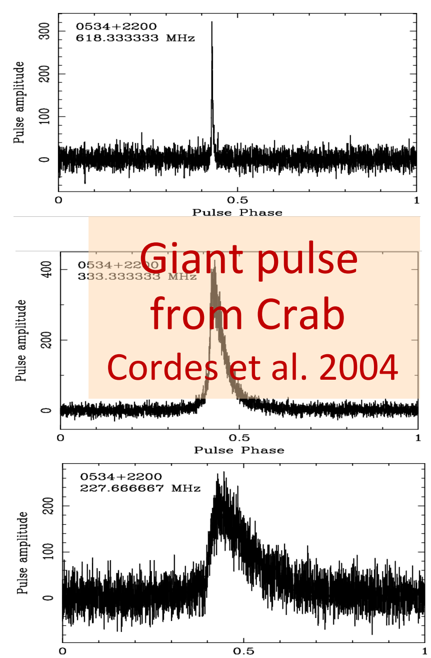
Time-domain universe zoo

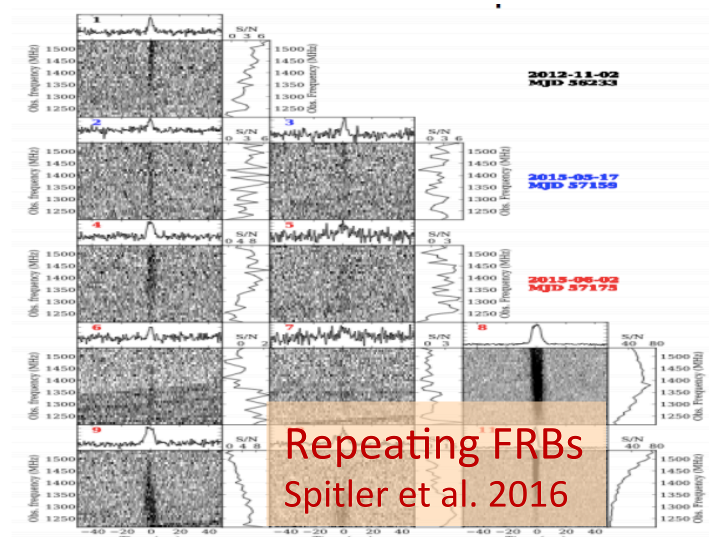




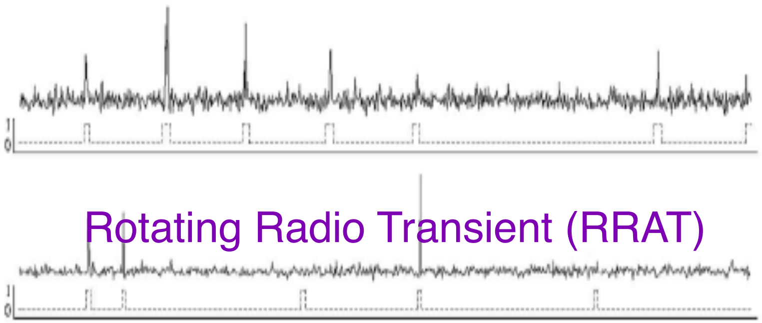


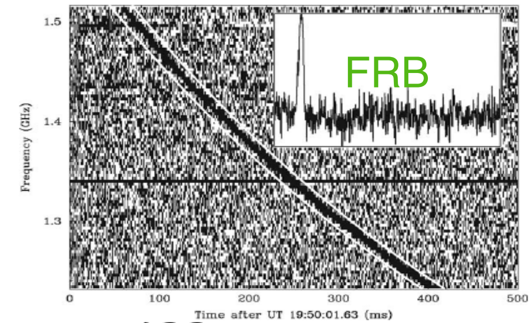


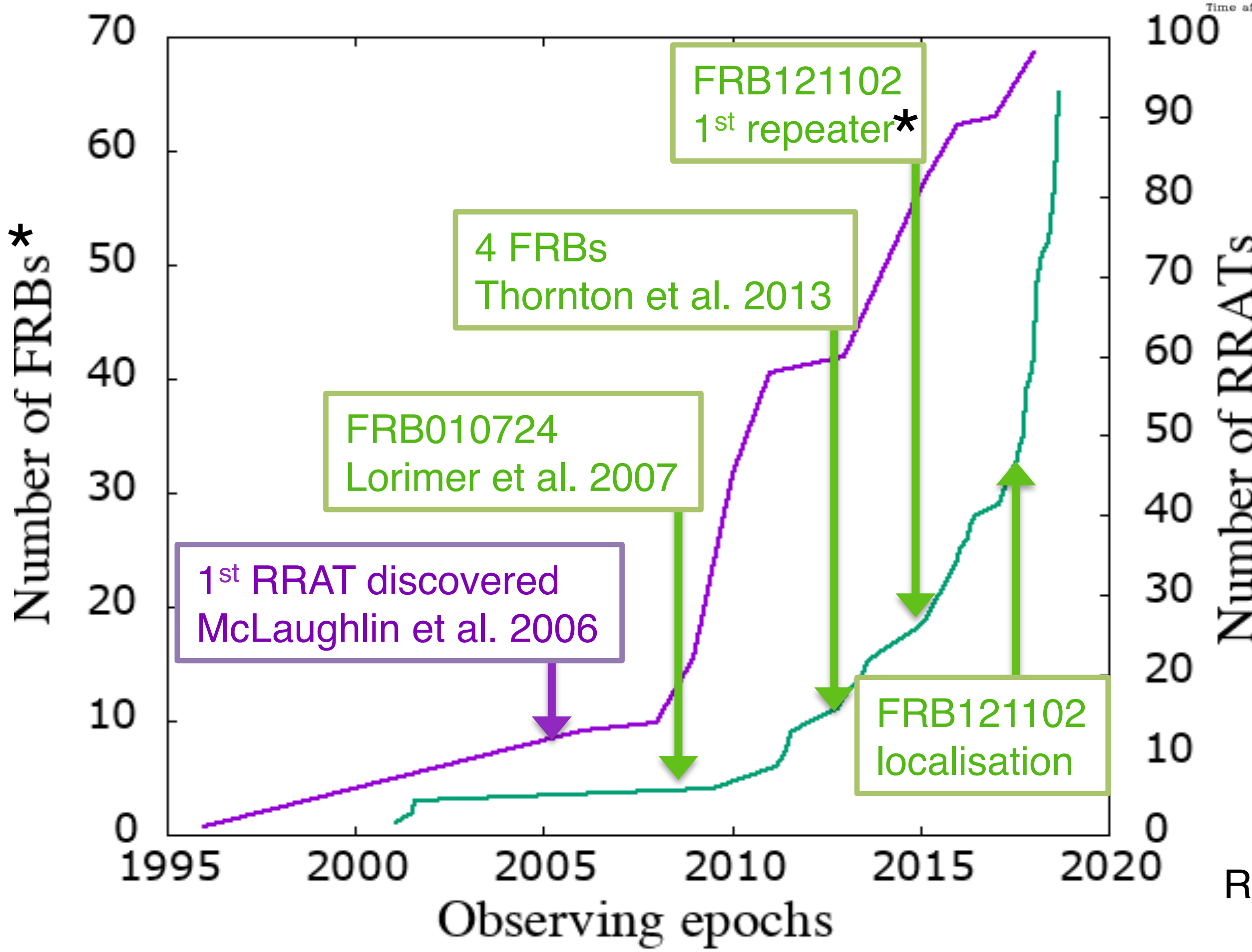




Fast Transients: FRBs and RRATs







Ref: psrcat, frbcat

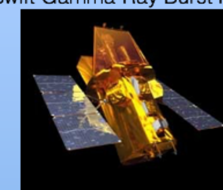
Fast Transients: Fast Radio Bursts

Millisecond duration radio bursts with likely extragalactic origin

- Only ~ 73 discovered so far (frbcat.org)
- Real-time detection with data capturing at full Nyquist domain for rapid follow-up to maximise science returns

Credit: Swinburne Astronomy Productions

Swift Gamma-Ray Burst Mission

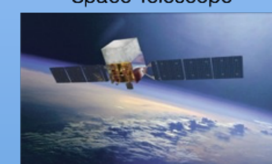


Credit: Swift

Chandra X-ray Observatory

Credit: NASA

Fermi Gamma-ray Space Telescope



Credit: NASA

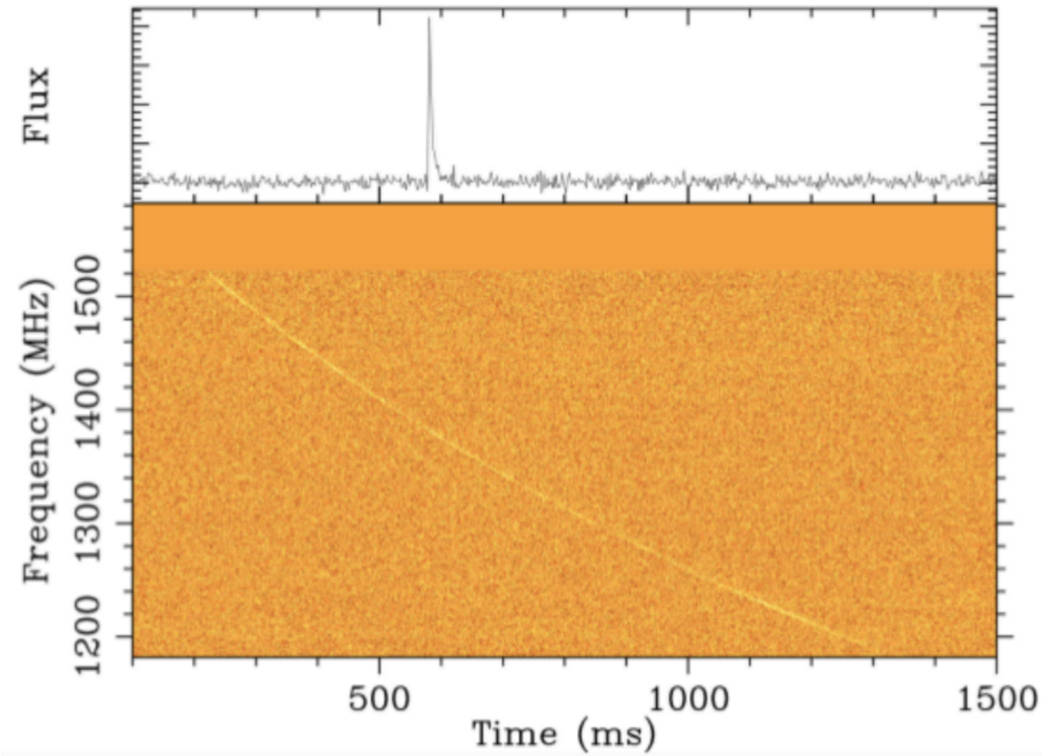
Subaru Telescope

Credit: Subaru Telescope

DECam at Blanco 4-m telescope

Credit: NOAO/AURA/NSF

Fast Radio Bursts: A dispersed single pulse



Dispersion measure

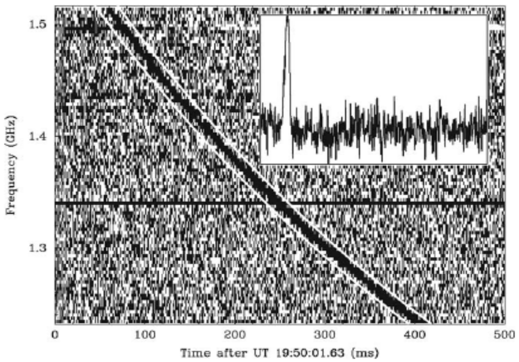
$$\mathrm{DM} = \int_0^d n_e(l)\,\mathrm{d}l.$$

Dispersion delay

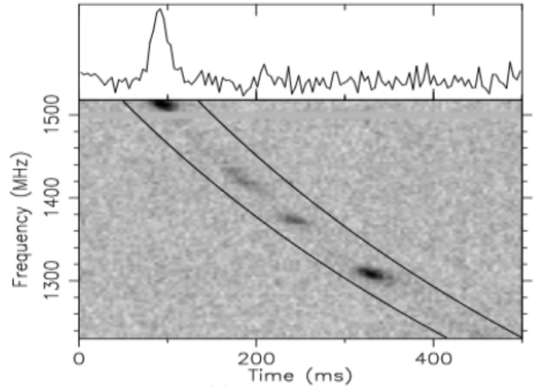
$$\Delta t = \frac{e^2}{2\pi m_e c}(\nu_{\mathrm{lo}}^{-2} - \nu_{\mathrm{hi}}^{-2})\ \mathrm{DM} \approx 4.15\,(\nu_{\mathrm{lo}}^{-2} - \nu_{\mathrm{hi}}^{-2})\ \mathrm{DM\ ms}$$

FRBs discovered over a DM range of 177 to 2596 pc cm^{-3}

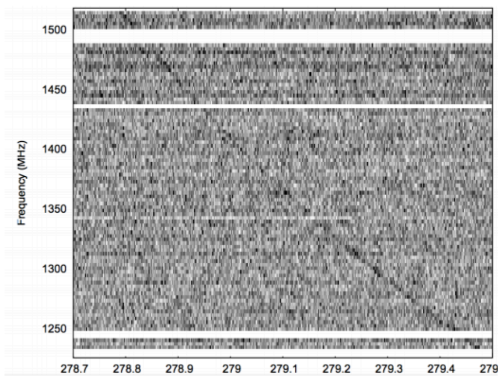
Fast Radio Bursts: A decadal journey



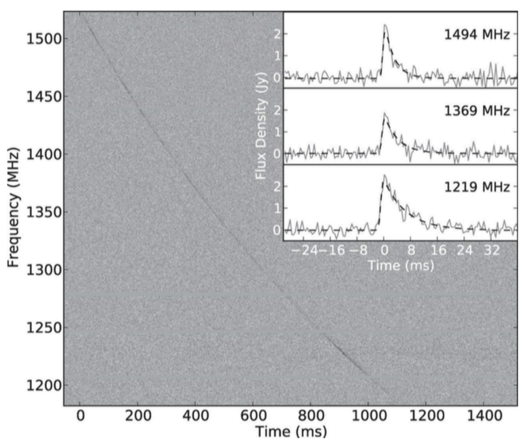
2007
Lorimer burst @ 375 pc cm^{-3}



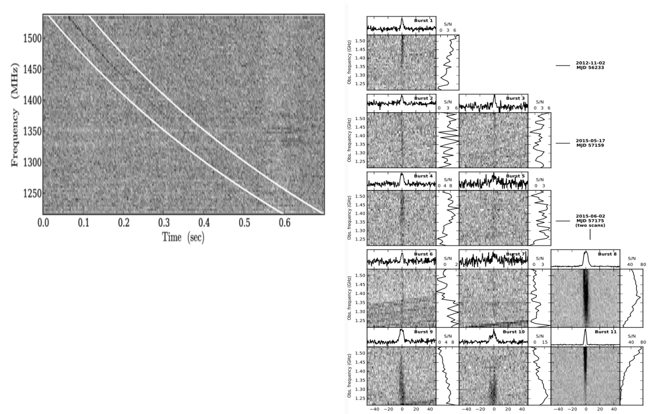
2011
Perytons @ Parkes



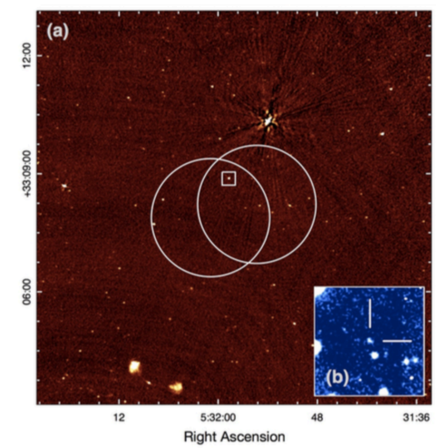
2013
Keane burst @ 746 pc cm^{-3}



2013
4 bursts by Thornton et al.

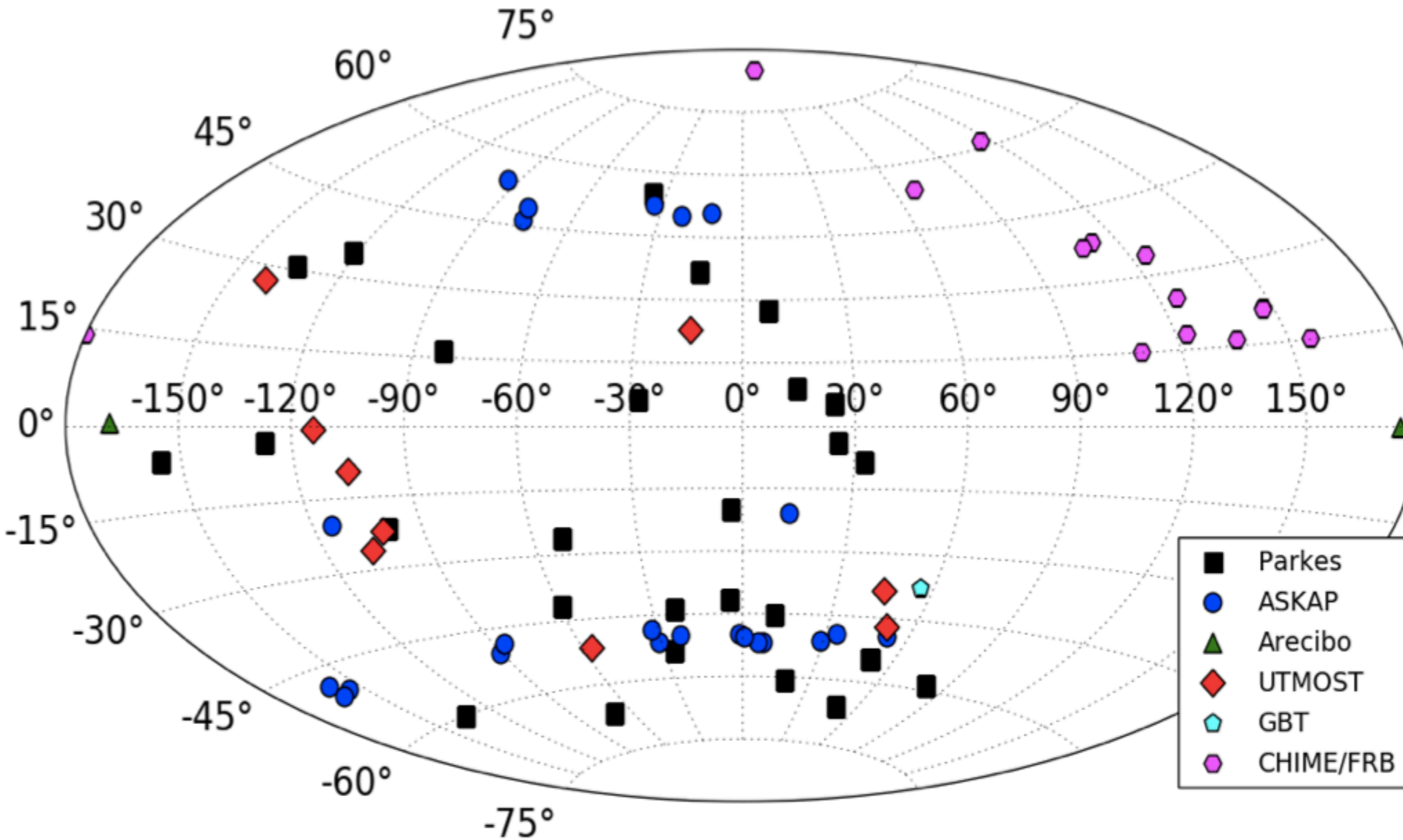


2014, 2016
Arecibo bursts by Spitler et al.



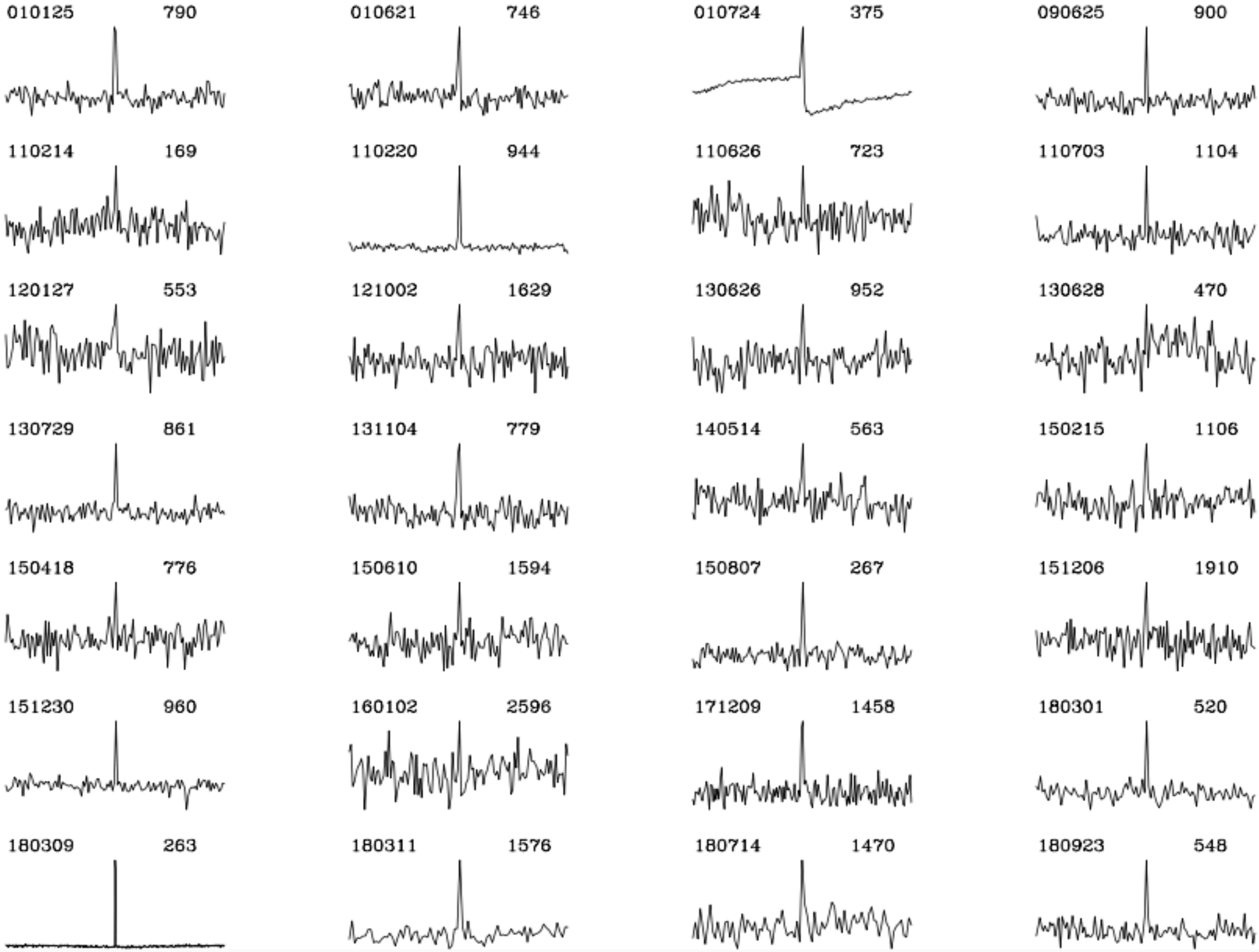
2017
Localisation by Chatterjee et al.

Fast Radio Bursts



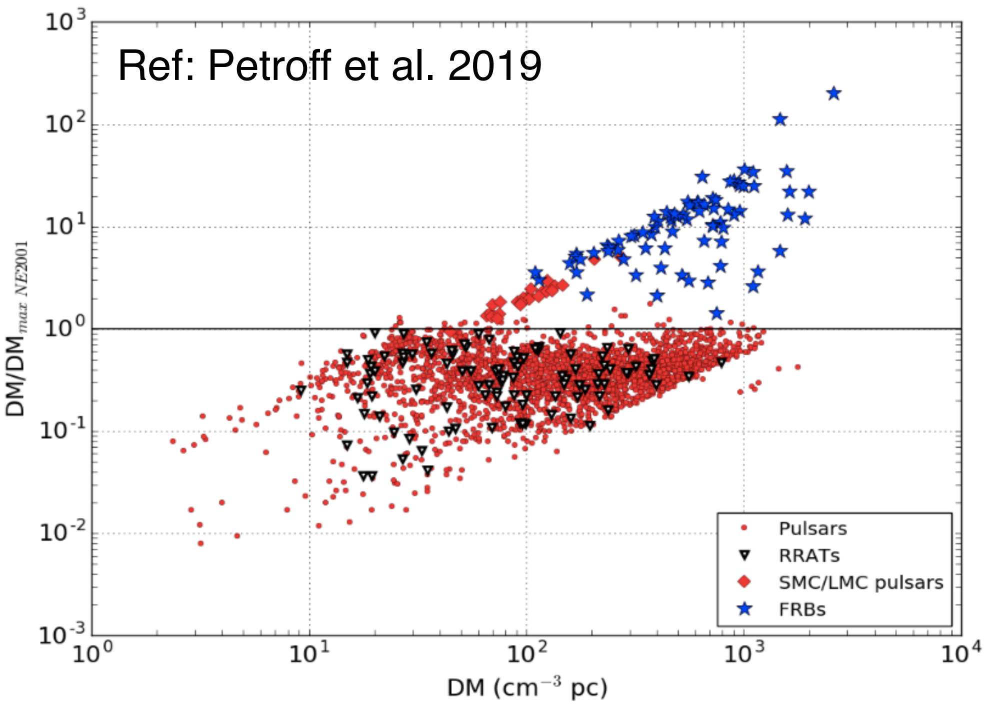
Ref: Petroff et al. 2019, frbcat.org

Fast Radio Bursts



Ref: Petroff et al. 2019, frbcat.org

Fast Radio Bursts: extragalactic origin



Excess DM

$$DM_E = DM - DM_{MW} = DM_{IGM} + \left(\frac{DM_{Host}}{1+z}\right)$$

DM_{MW}: Galactic contribution (NE2001)
DM_{IGM}: Intergalactic medium contribution
DM_{Host}: Host galaxy contribution

Redshift estimation from DM

$Z < DM/1000\ cm^{-3}\ pc$

Source luminosity $L = \frac{4\pi d_L^2 S_\nu \Delta\nu}{(1+z)}$

For a FRB at DM of 563 pc cm^{-3} with peak flux density of 1 Jy, luminosity distance $d_L < 3.3$ Gpc

for $z < 0.56$; luminosity limit over 300 MHz band bandwidth ~ O(10^{42}) erg/s

Normal Radio pulses with ~ ms to 10s μs duration having energy ~ O(10^{30}) erg/s

Giant pulses from Crab with ~ μs duration having energy ~ O(10^{36}) erg/s

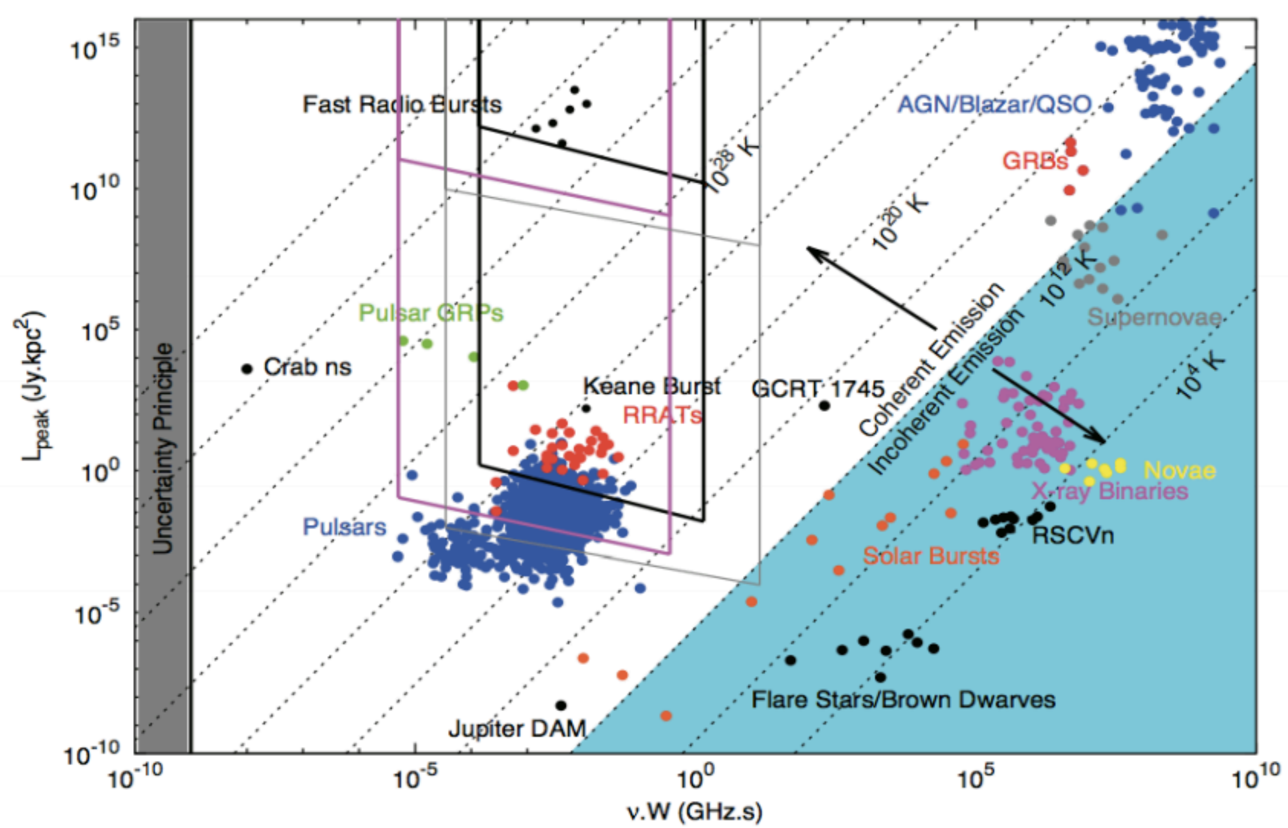
GRBs with ~ sec duration having energy ~ O(10^{51}) erg/s

Fast Radio Bursts: brightness

Brightness temperature is an indicator of non-thermal origin of the emission

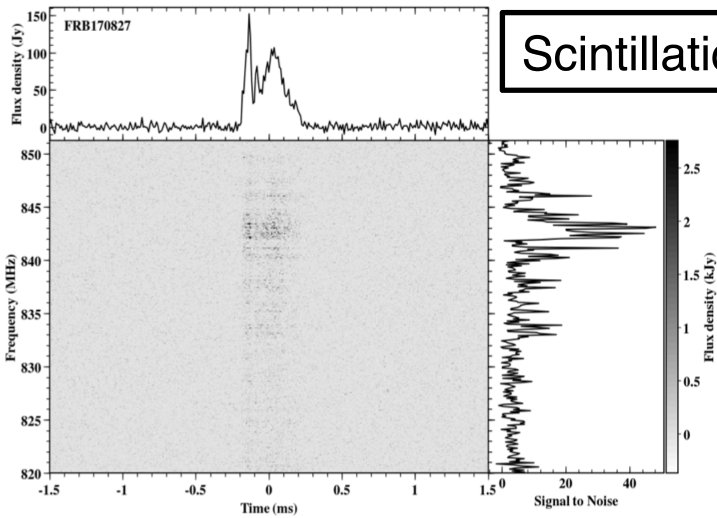
$$T_{\rm B} \simeq 10^{36}\ {\rm K} \left(\frac{S_{\rm peak}}{\rm Jy}\right) \left(\frac{\nu}{\rm GHz}\right)^{-2} \left(\frac{W}{\rm ms}\right)^{-2} \left(\frac{d_L}{\rm Gpc}\right)^{2}$$

FRBs are at $T_B \sim 10^{35}$ K; Radio Pulsars are at 10^{26} K; Crab nanoshots are at $\sim 10^{37}$ K



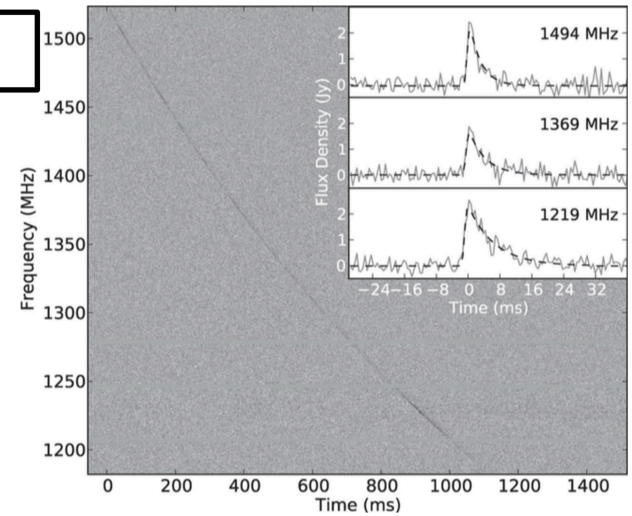
Fast Radio Bursts: propagation effects

Farah et al. 2018



Scintillation

Scattering



Thronton et al. 2013

Scintillation caused by diffraction and refraction of the incoming signal through clumpy, turbulent medium

The characteristics frequency scale of scintillation strongly frequency-dependent

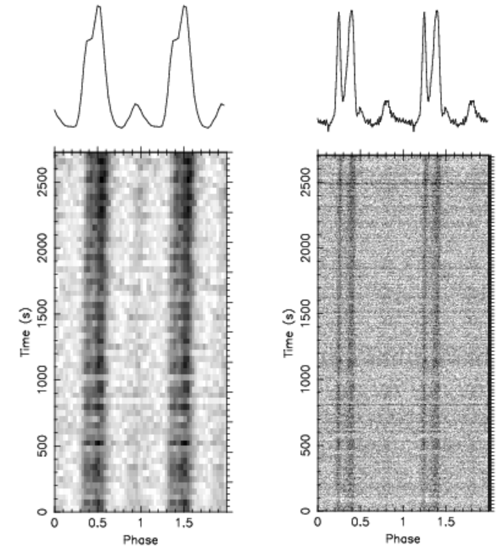
Spectral feature seen in FRBs: propagation effect or intrinsic: narrow-spectral structure Vs broad spectral structure

FRB signals temporally broadened by scattering caused by multi-path propagation

Scattering time-scale ∝ ν^{-4}

Searching for Fast Radio Bursts

Noise in the data $$\sigma_S = \frac{T_{\rm sys}}{G\sqrt{2\,\Delta\nu\, t_{\rm samp}}}$$



De-dispersion: Incoherent Vs Coherent dedispersion

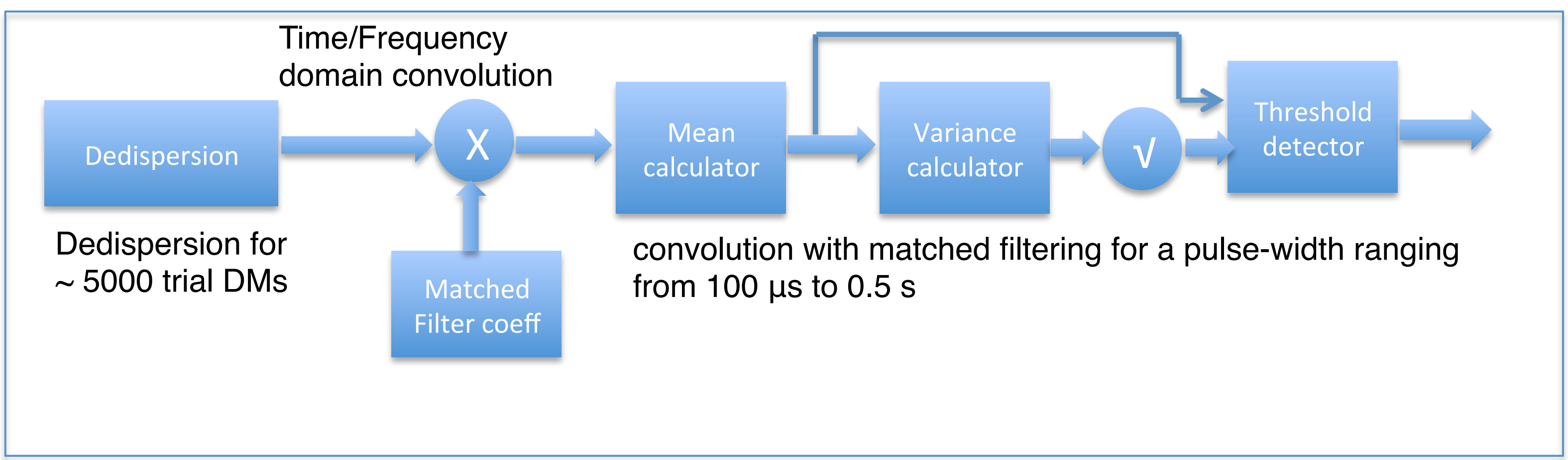
Residual smearing in incoherent dedispersion

$$\Delta t_{\rm DM} = 8.3 \times 10^6\, {\rm DM}\, \Delta\nu_{\rm ch}\, \nu^{-3}\ {\rm ms}$$

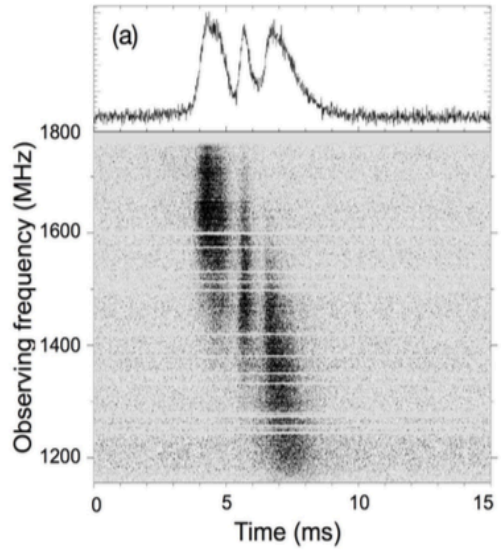
Detected width of FRB pulse

$$W = \sqrt{W_{\rm int}^2 + t_{\rm samp}^2 + \Delta t_{\rm DM}^2 + \Delta t_{\rm DMerr}^2 + \tau_{\rm s}^2}$$

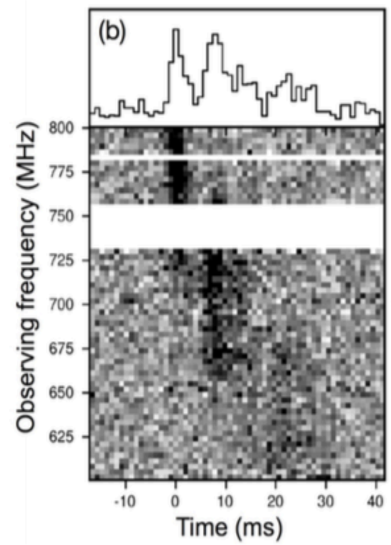
Detection Strategy



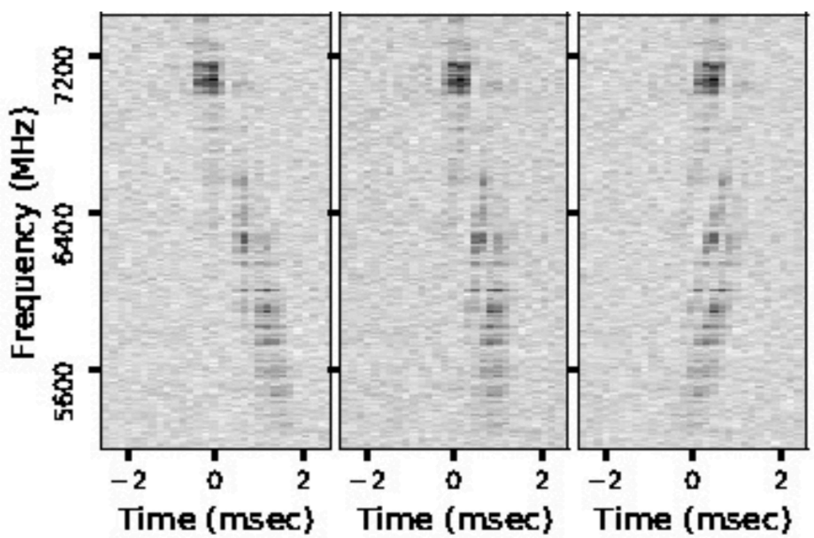
Fast Radio Bursts: Repeating ones



FRB 121102



FRB 180814.J0422+73



FRB 121102, Michilli et al. 2018

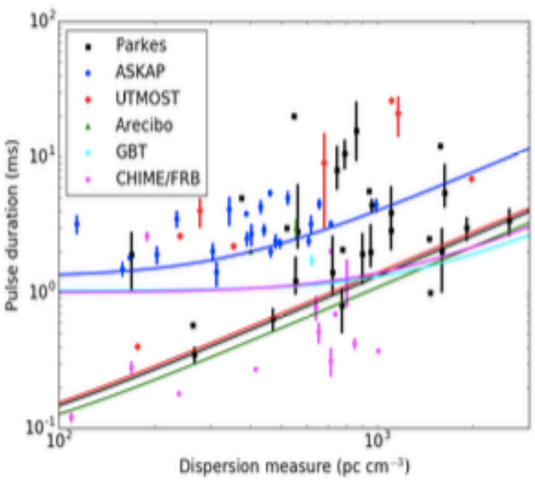
Sub-burst structures with descending centre frequencies over time

Frequency structure from propagation effect can not change in ~ sub-ms time-scale

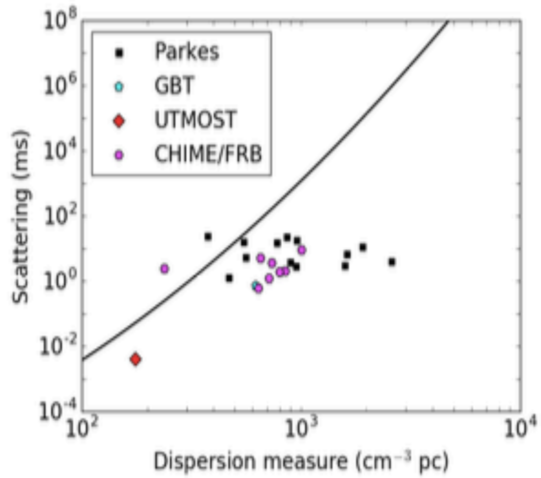
Scintillation can explain higher resolution (few MHz) spectral structures (narrow decorrelation bandwidth for FRBs)

Both repeaters have similar structure→ Intrinsic to emission rather than propagation

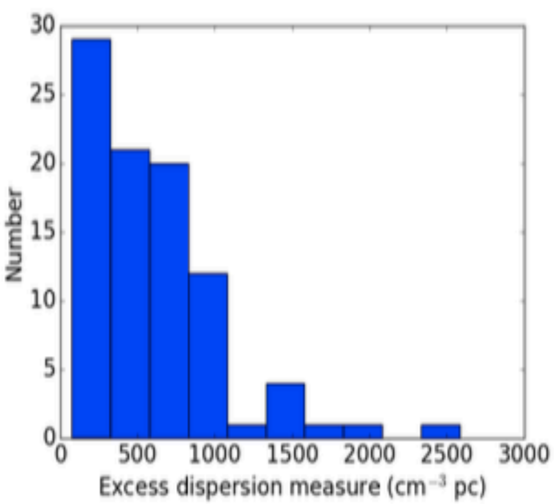
Fast Radio Bursts: Width and Scattering



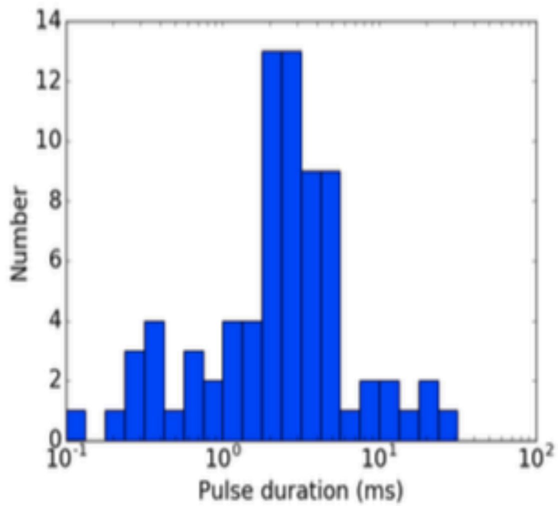
(a) Width vs. DM



(b) Scattering vs. DM



(c) DM excess histogram



(d) Pulse duration histogram

Petroff et al. 2019

Widths of FRBs as function of DMs along with the predictions from DM smearing

Scattering of FRBs as function of DMs → FRBs are under-scatter than the Galactic pulsars at similar DMs → IGM plays minor role in scattering

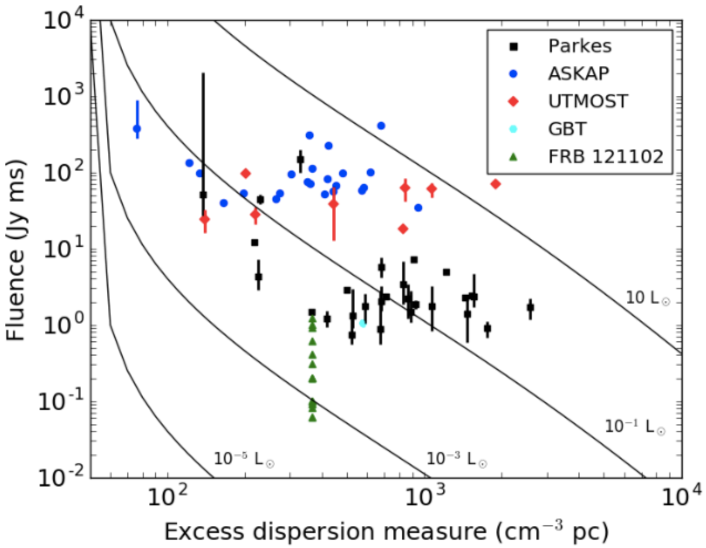
The largest DM observed is 2596 pc cm^{-3} → redshift of 2.1

FRB pulse width of 10 μs (limit on emitting region) to 26 ms (limit on propagation effects).

→ require real-time detection and triggering for Nyquist resolution data dump

Fast Radio Bursts: event rates

Petroff et al. 2019



Newer bursts from ASKAP are brighter and closer than the previous Parkes bursts

An order of magnitude spread in the intrinsic luminosity

In addition to surveys (using FAST) to probe fainter high-DM end, we also *need to probe bright low-DM part.*

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)

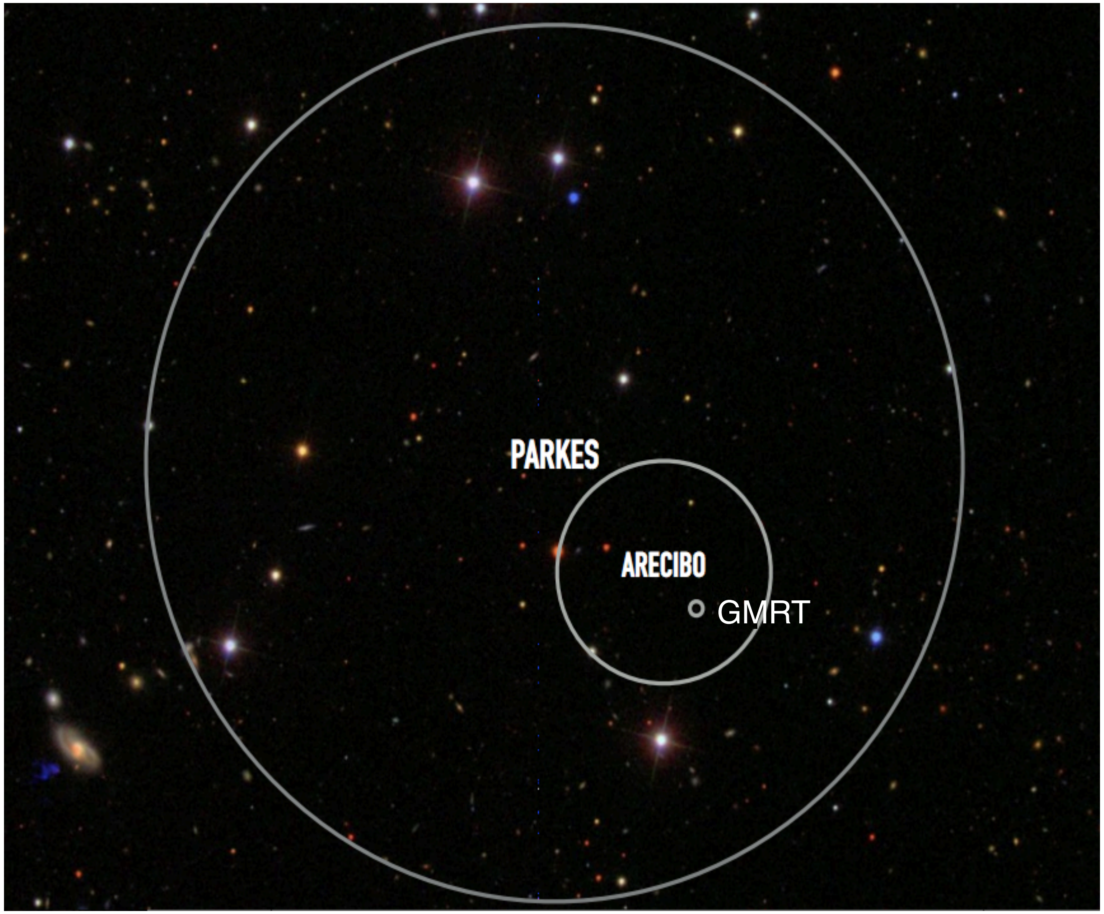
On-average > 10^3 FRBs / sky every day above a F > 1 Jy-ms

Fast Radio Bursts: localisation

FRBs are localised to host galaxies → specific galaxies, distance from the center can be probed

Independent redshift measurement

Search for multi-wavelength prompt emission or afterglow requires *(quasi) real-time localisaion of FRBs (@ few arc-sec) triggered by real-time detection*



Fast Radio Bursts: possible progenitors

Propose FRB sources based on energetic, time scale and event rate

Natural association with neutron stars due to high energy and short time-scale

Super giant pulses from young pulsars; nulling pulsars, RRATs at their extreme limits

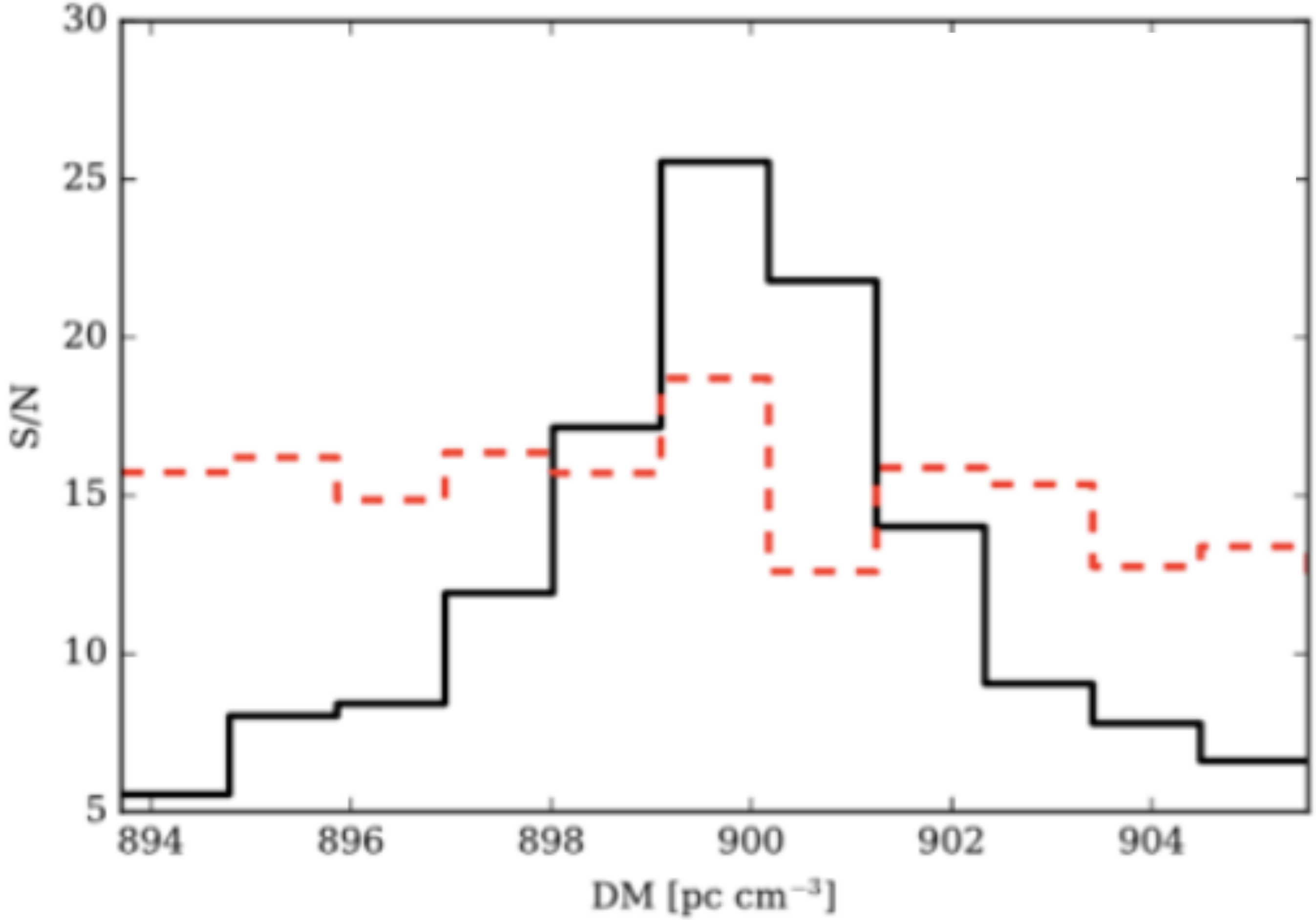
Repeating pulses from Magnetar (in dense supernova environment), where the radiated energy is drawn from the neutron star's magnetostatic energy

Neutron star mergers have sufficient energy to power FRBs, event rate several order magnitude lower → multi-wavelength prompt emission or afterglows

Cataclysmic model involves collapse of a supermassive neutron start to a black hole

FRBs from the interaction of jet from an active galactic nucleus and surrounding turbulent medium

FRB Vs RFI?



GMRT High Resolution Southern sky (GHRSS) Survey

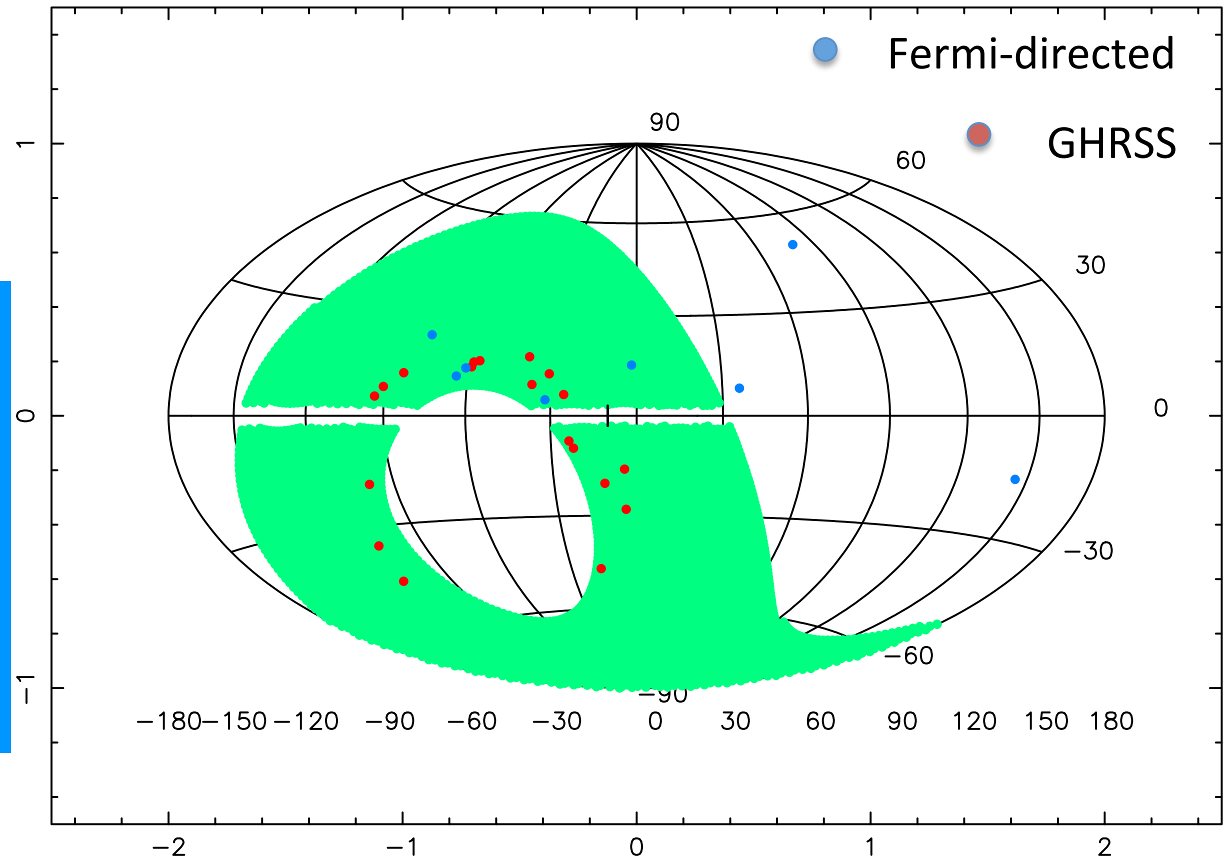
Team: Bhattacharyya, Roy, Stappers, Keith, McLaughlin, Ray, Ransom, Chengalur, Lyne, Sally, Mateusz, Sanjay

Target Sky

Entire southern sky visible to GMRT (Dec 0 to -54)

Periodicity Search
18 pulsars (started 2014)
2 MSPs
2 mildly recycled pulsars
1 with γ-ray emission

5 pulsars with uGMRT



1st MSP from uGMRT

1st RRAT from GMRT

Bhattacharyya et al. 2016,
Astrophysical Journal, 817, 130

Bhattacharyya et al. 2019,
Astrophysical Journal (under review)

Webpage :
www.ncra.tifr.res.in/ncra/research/research-at-ncra-tifr/research-areas/pulsarSurveys/GHRSS

Current time-domain surveys

Table 1. A summary of some of the ongoing pulsar surveys sensitive to millisecond pulsars and those on the near horizon.

telescope	name	frequency (MHz)	status
Arecibo	PALFA	∼1400	ongoing [23]
Arecibo	drift scan	∼350	ongoing [24]
Effelsberg	HTRU-N	∼1400	ongoing [25]
FAST	targeted	wide band	started (http://crafts.bao.ac.cn/pulsar/fast_all_pulsar_list/)
FAST	wide area	∼1400	started (http://crafts.bao.ac.cn/pulsar/fast_all_pulsar_list/)
GBT	GBNCC	∼350	ongoing [26]
GMRT	GHRSS	∼325	ongoing [27]
LOFAR	LOTAAS	∼150	ongoing (http://www.astron.nl/lotaas/)
LOFAR	DRAGNET	∼150	ongoing [28]
MeerKAT	TRAPUM	∼1400/3000	in preparation (http://trapum.org)
Parkes	HTRU-S	∼1400	complete, processing ongoing [29]
Parkes	SUPERB	∼1400	ongoing [30]
targeted	Fermi UIDs	various	ongoing (http://tinyurl.com/fermipulsars/)

Stappers et al. 2018

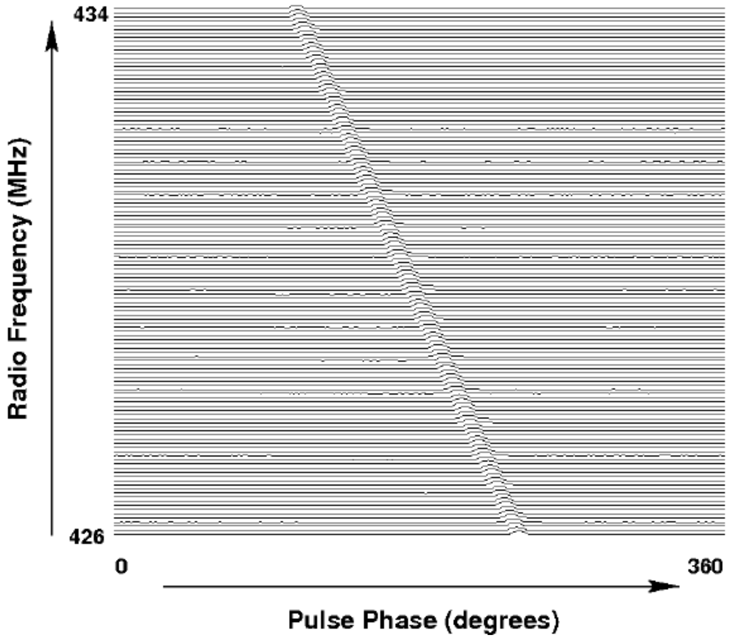
Pulsar/FRBs searches at Low and Mid radio frequencies

Low and Mid can probe different pulsar population

- Low: 100 – 500 MHz
  - Local population with low DM (dispersion ∞ ν^{-2})
  - Steep spectra sources (α ∞ $\nu^{-1.5}$)
  - Sensitive away from plane at higher Galactic latitude
  - Scattering can be of concern (scattering ∞ ν^{-4})
  - Higher survey speed (FOV ∞ ν^{-2}) → less beams

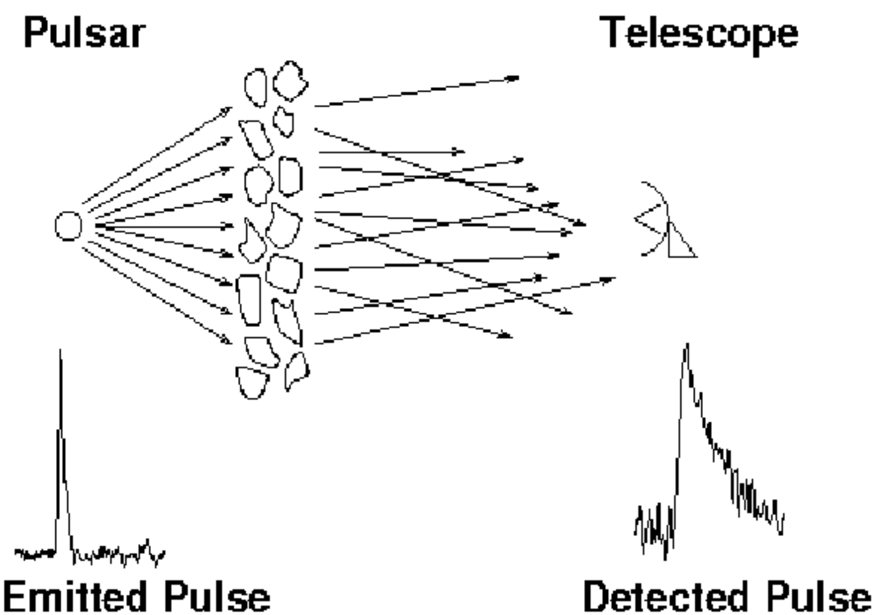
- Mid: 600 MHz – 1.5 GHz
  - Probing population at higher DM
  - Sources with less steep spectral indices
  - Less scattering
  - Sensitive probe for sources close to Galactic plane
  - More survey beams needed

Observational challenges



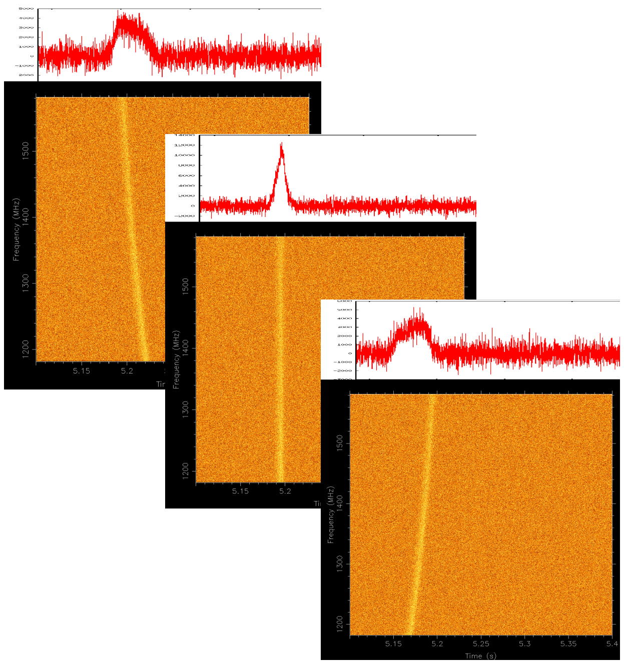
Dispersion removal : dedispersed the data many “trial” DMs

Scattering : survey at higher frequency near the Galactic plane



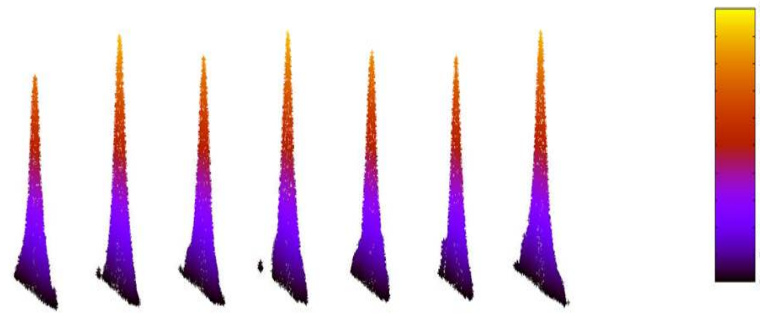
FRB search a computational problem

Many frequency dependent delay sweep: *dedispersion* trials



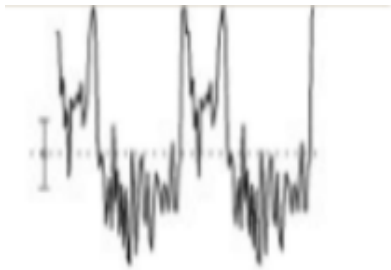
Operations ~ N_{DM} * BW * T_{obs}

Large number of *convolution* trials

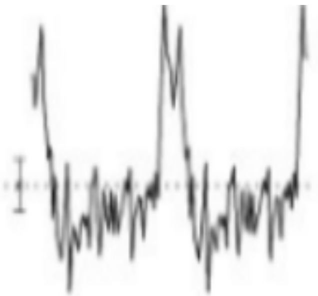


Operations ~ N_{DM} * (N_{width}) * T_{obs}

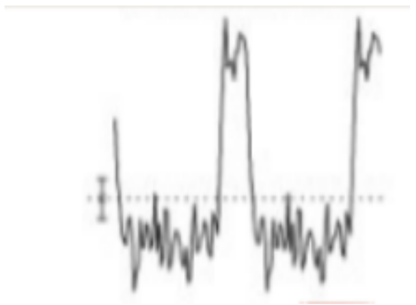
Which one is correctly de-convolved?



FRB-A



FRB-B



FRB-C

Real-time FRB search pipeline for GHRSS

- A GPU-based FRB detection pipeline for the GMRT (using AstroAccelerate credit: Wes et al.) → 1st RRAT from GMRT discovered!!
- GMRT beams can be processed in (5x faster than) real-time for DM up to 2000 pc cm^{-3} (up to z=2)