Searches for Radio Transients Prospects & Challenges with SKA

--desh

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0. The radio “transient story” so far
1. Transient searches : optimizations
2. Single-pulse searches (potential at low frequencies, examples @ Gauribidanur)
3. MWA related development
4. Multi-band approach
5. Summary

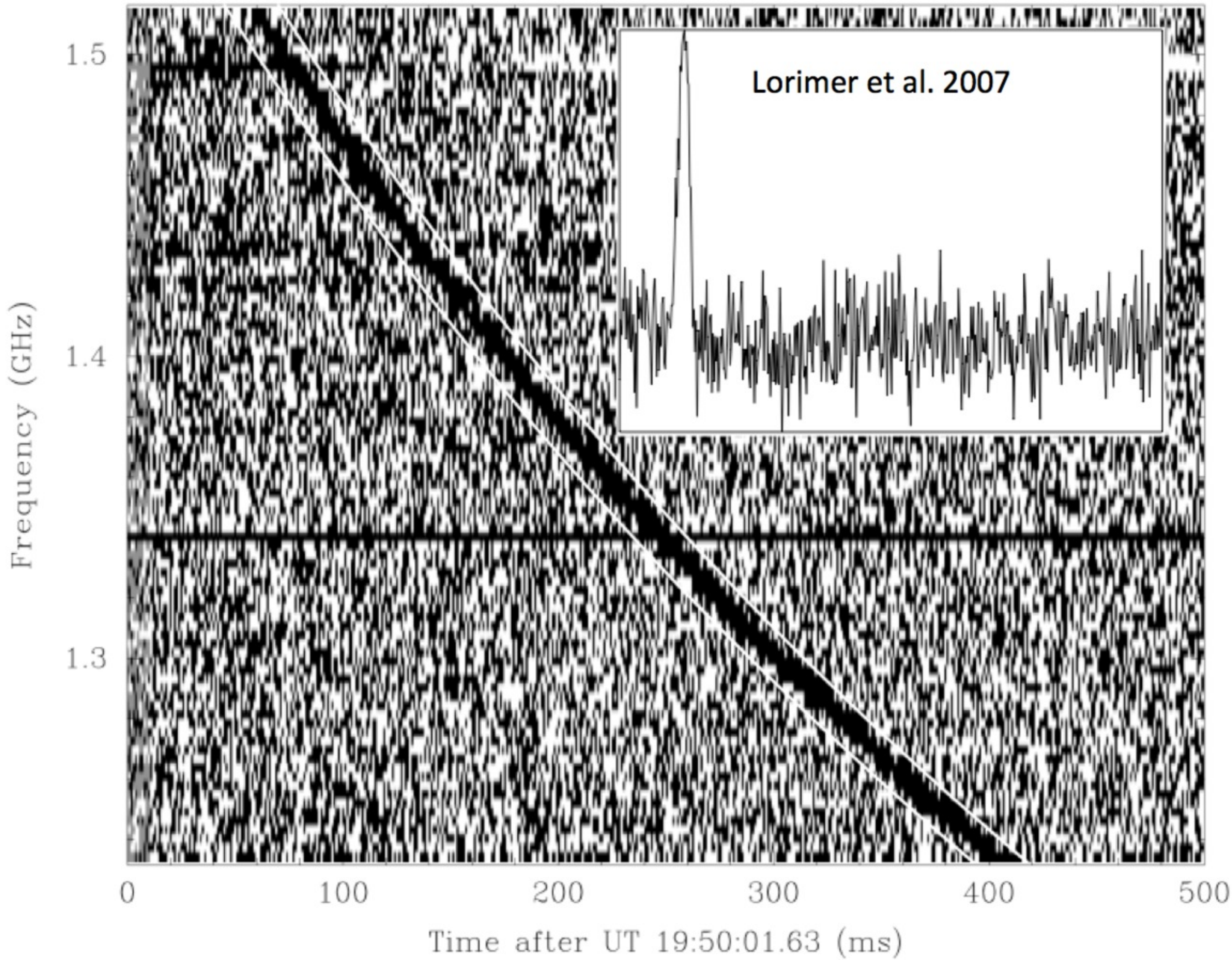
=====Transients have been searched for quite some time, but the recent story starts with.. the so-called “Lorimer Burst” (2007) reported from the Parkes Telescope
.... detection of a dispersed pulse

Table 2
Survey Parameters

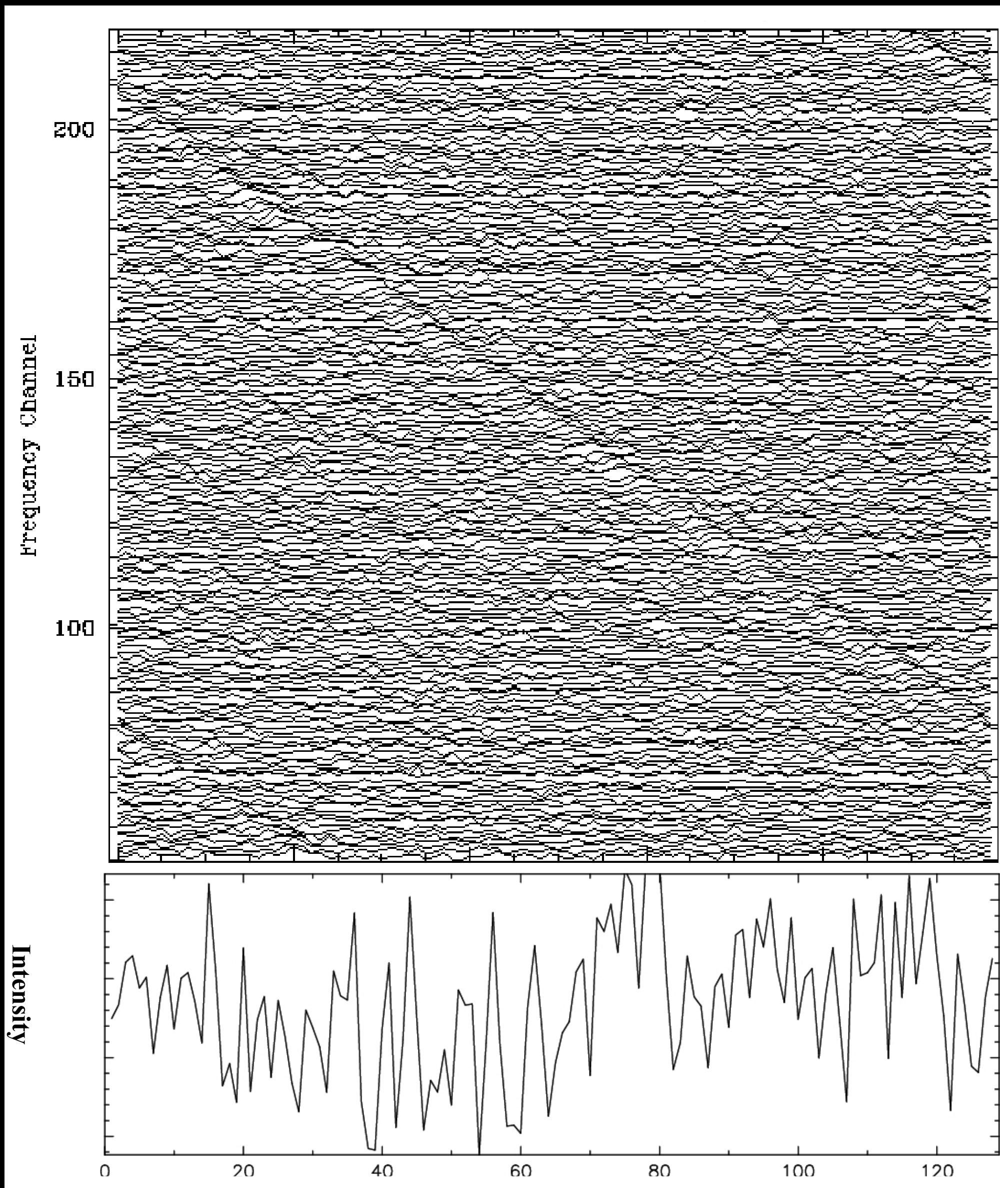
No.	Author	Telescope	Year	Dedisp	Ref	ν_c (MHz)	m	T_R (K)	$t_{\rm sample}$ (μs)	t (μs)
1	O'Sullivan et al.	Dwingeloo	1978	incoh	1	5000	(6)	65	2	2700
2	Phinney & Taylor	Arecibo	1979	incoh	2	430	6	175	1.7×10^4	1.7×10^4
3	Amy et al.	MOST	1989	incoh	3	843	(6)	...	1	1.7×10^4
4	Katz & Hewitt	STARE	2003	incoh	4	611	5	150	125000	125000
5	McLaughlin et al.	Parkes	2006	incoh	5, 6	1400	5	21	250	250
6	Lorimer & Bailes	Parkes	2007	incoh	7	1400	(6)	21	1000	1000
7	Deneva et al.	Arecibo	2008	incoh	8	1440	5	30	64	64
8	Von Korff et al.	Arecibo	2009	coher	...	1420	30	30	0.4	0.4

No.	$\Delta\nu$ (MHz)	G (K Jy^{-1})	Beam Ω	Beams	$t_{\rm obs}$ (h)	$N_{\rm pol}$	Sens (Jy μs)	$d_{\rm max}$ (kpc)	Rate (pc^{-3} yr^{-1})
1	100	0.1	6.6×10^{-5}	1	46	1	2×10^4	61	3.8×10^{-7}
2	16	27	6.6×10^{-5}	1	292	1	1300	240	9.4×10^{-12}
3	3	...	3.6×10^{-8}	32	4000	1	1.6×10^{3} [a]	22	5.6×10^{-7}
4	4	6.1×10^{-3}	1.4	1	13000	2	1.5×10^5	0.22	1.3×10^{-7}
5	288	0.7	1.3×10^{-5}	13	1600	2	99	870	1.5×10^{-13}
6	288	0.7	1.3×10^{-5}	13	480	2	240	560	1.8×10^{-12}
7	100	10	8.1×10^{-7}	7	420	2	8.5	3000	4.2×10^{-13}
8	2.5	10	8.1×10^{-7}	7	1540	1	55	1200	1.9×10^{-12}

Notes. Parentheses around a value indicate that we assume this value because we could not deduce one from the original paper.
[a] MOST has 1 mJy of noise in each beam after 12 hr, http://www.physics.usyd.edu.au/sifa/Main/MOST.
References. (1) O'Sullivan et al. 1978; (2) Phinney & Taylor 1979; (3) Amy et al. 1989; (4) Katz et al. 2003; (5) McLaughlin et al. 2006; (6) Manchester et al. 2001; (7) Lorimer & Bailes 2007; (8) Deneva et al. 2009.


Lorimer et al. 2007
Frequency (GHz)
1.5
1.4
1.3
0
100
200
300
400
500
Time after UT 19:50:01.63 (ms)

Effects of Dispersion and its Correction

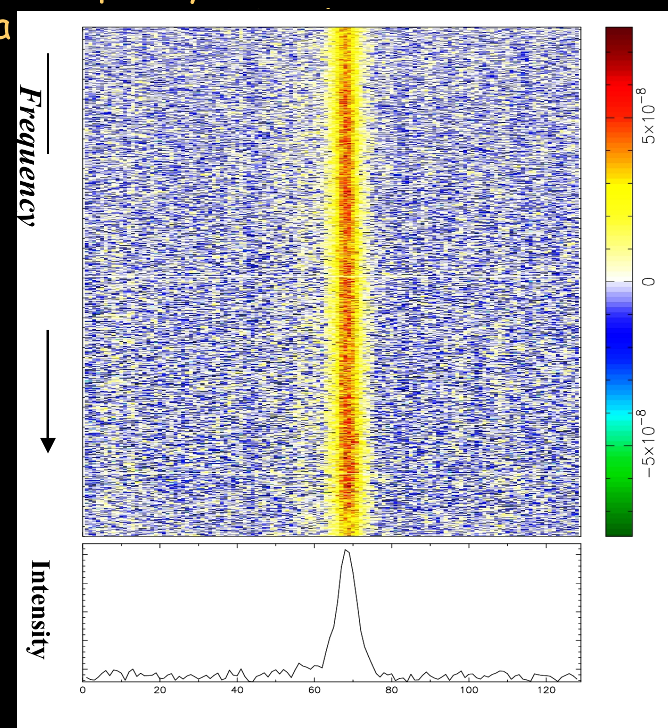


ν = 1420 MHz, $\Delta\nu$ = 32 MHz

$\Delta t/DM$ << 1 msec ;

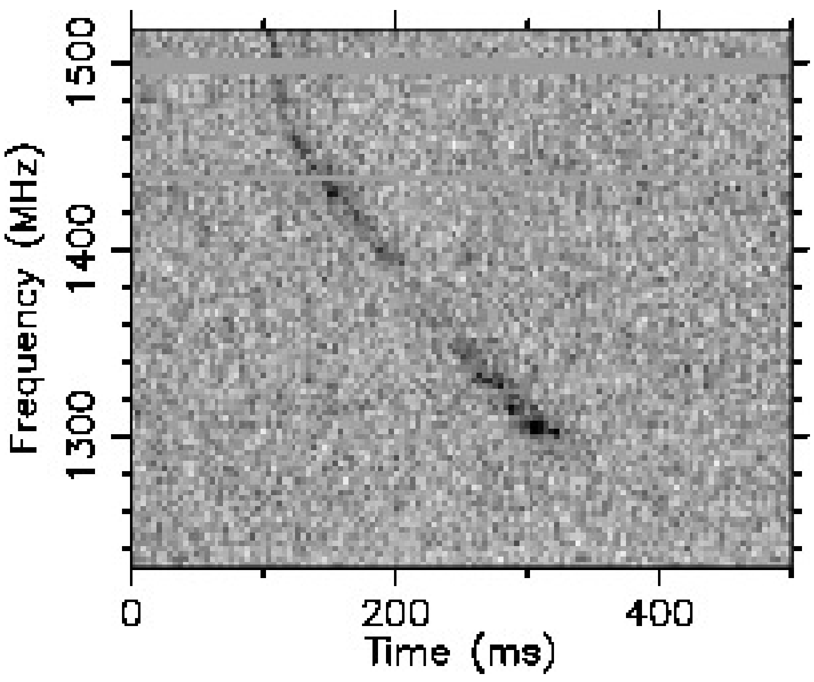
ν = 35 MHz, $\Delta\nu$ = 1 MHz,
$\Delta t/DM$ ~ 200 msec ;

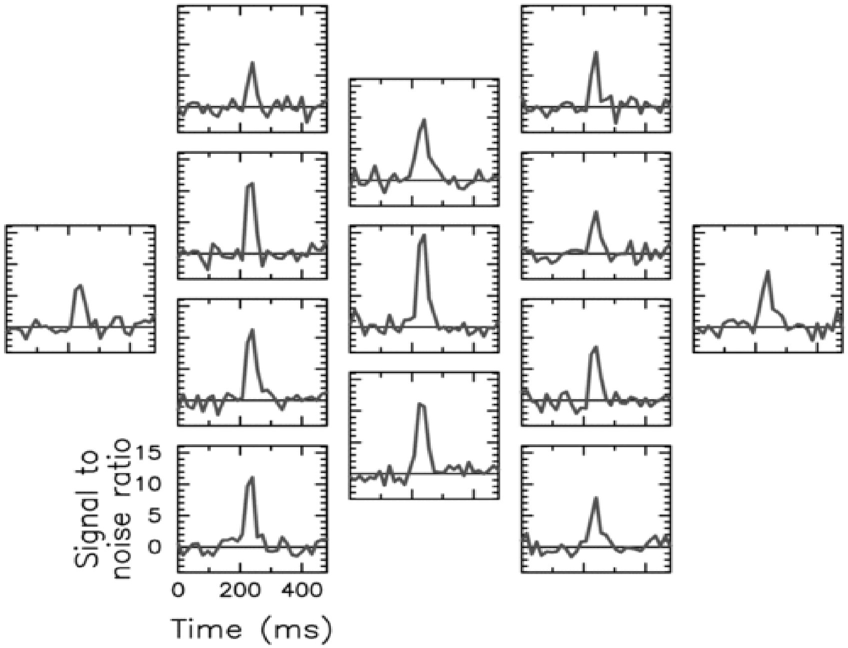
- **Incoherent (Post-detection) dedispersion:** Signal time sequence from each frequency channel is shifted backwards by a



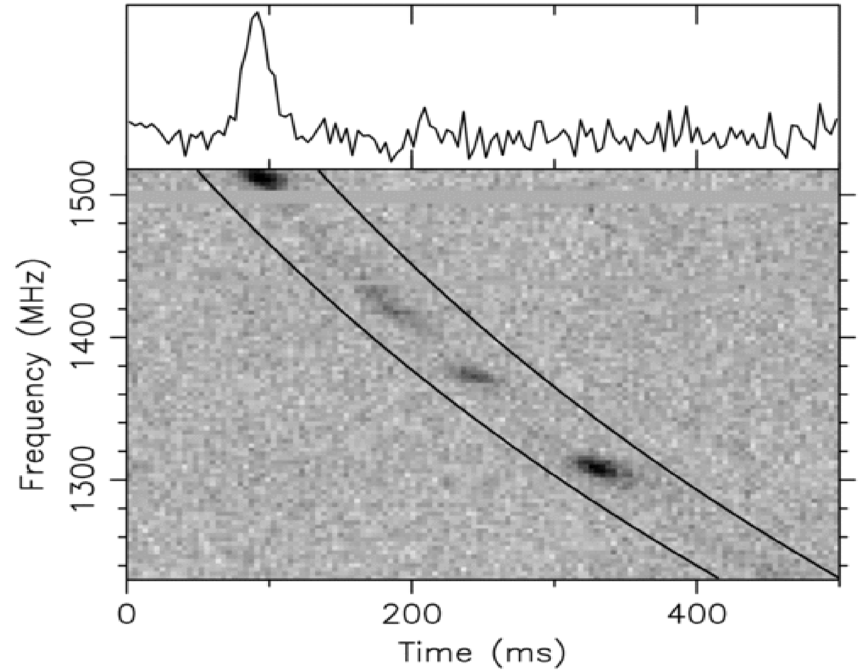
"Radio Bursts with Extragalactic Spectral Characteristics Show Terrestrial Origins"

.....Sarah Burke-Spolaor et al 2010

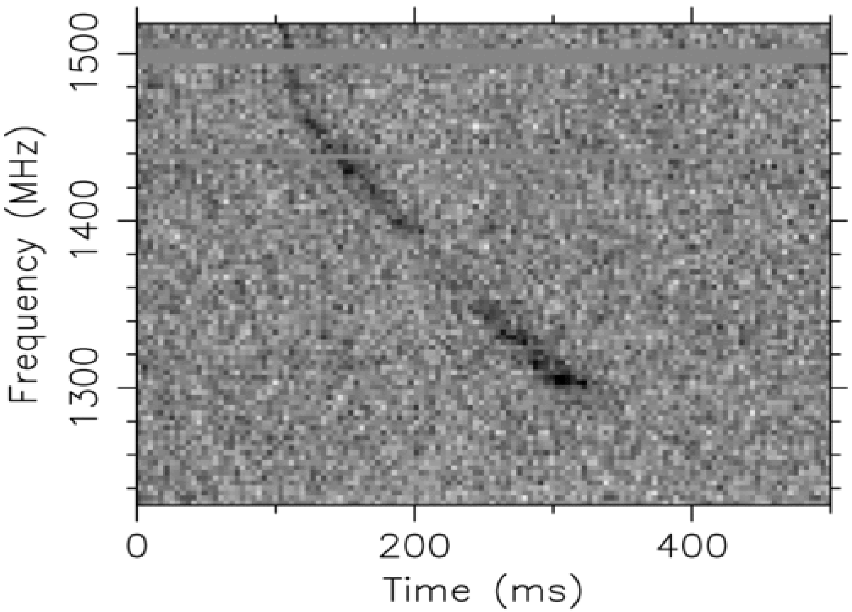




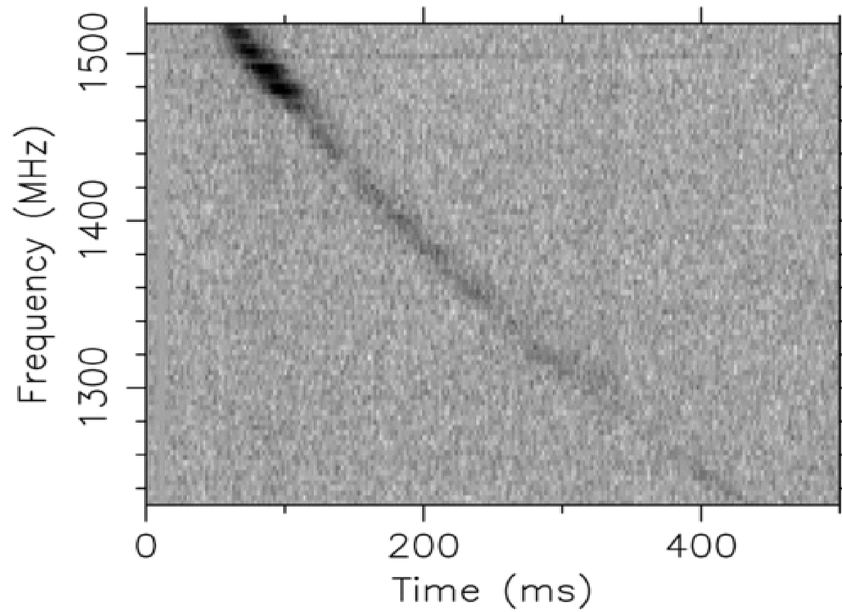
(a) Peryton 08 in 13 beams



(b) Peryton 08

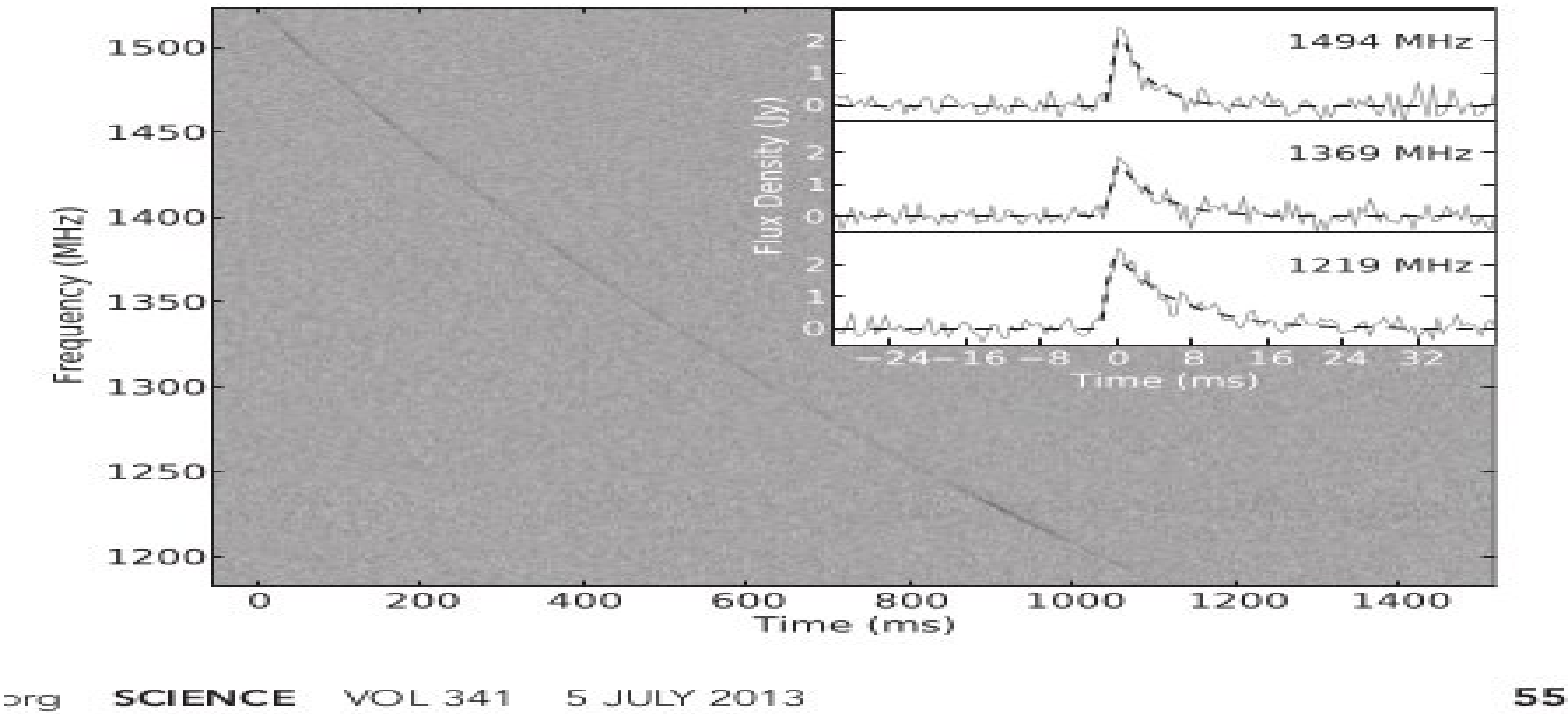


(c) Peryton 06



(d) Peryton 15

Lorimer burst like
recent Fast-Radio-Bursts (FRBs)



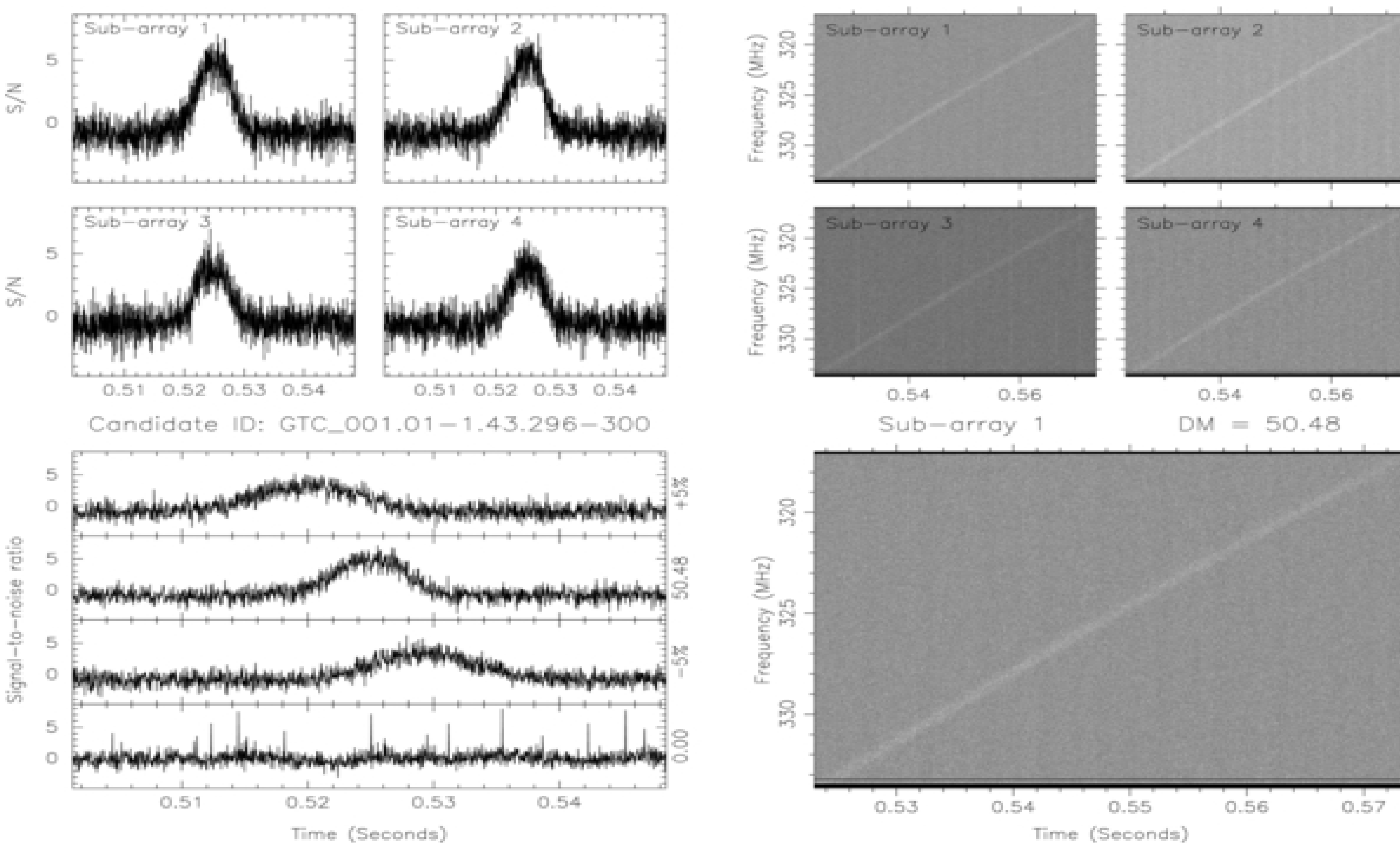
Thornton et al. 2013

If real, expect several hundreds per day !! ..~20 till now

Extra-galactic origin ?!!

	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam right ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam declination (J2000)	−12° 24′	−44° 44′	−02° 52′	−18° 25′
Galactic latitude, b (°)	−54.7	−41.7	−59.0	−66.2
Galactic longitude, l (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy hh:mm:ss.sss)	20/02/2011 01:55:48.957	27/06/2011 21:33:17.474	03/07/2011 18:59:40.591	27/01/2012 08:11:21.723
DM (cm^{-3} pc)	944.38 ± 0.05	723.0 ± 0.3	1103.6 ± 0.7	553.3 ± 0.3
DM_E (cm^{-3} pc)	910	677	1072	521
Redshift, z (DM_{Host} = 100 cm^{-3} pc)	0.81	0.61	0.96	0.45
Co-moving distance, D (Gpc) at z	2.8	2.2	3.2	1.7
Dispersion index, α	−2.003 ± 0.006	–	−2.000 ± 0.006	–
Scattering index, β	−4.0 ± 0.4	–	–	–
Observed width at 1.3 GHz, W (ms)	5.6 ± 0.1	<1.4	<4.3	<1.1
SNR	49	11	16	11
Minimum peak flux density S_ν (Jy)	1.3	0.4	0.5	0.5
Fluence at 1.3 GHz, F (Jy ms)	8.0	0.7	1.8	0.6
$S_\nu D^2$ (× 10^{12} Jy kpc^2)	10.2	1.9	5.1	1.4
Energy released, E (J)	$\sim 10^{33}$	$\sim 10^{31}$	$\sim 10^{32}$	$\sim 10^{31}$

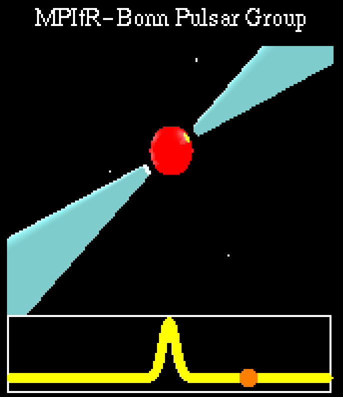
GMRT effort … pipeline ready… use of sub-arrays

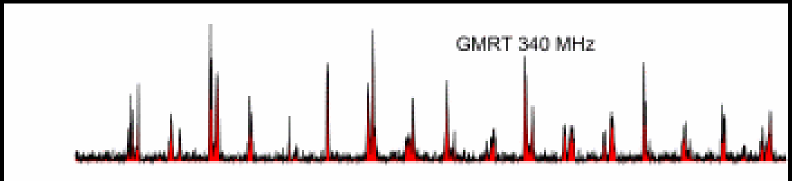


Potential Sources of Fast Radio Transients

- Pulsars : more in the post-tea pulsar talk

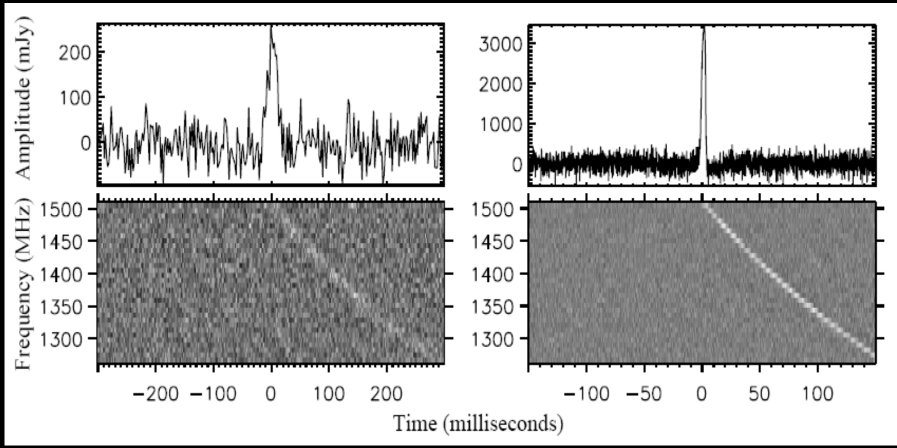
Found so far ~ 2000
Expected number is much greater than this
(The Crab Pulsar was found due to its giant pulses)





2. RRATs :

A new category of radio sources (McLaughlin, M. A., 2006)
Not explored much at low frequencies



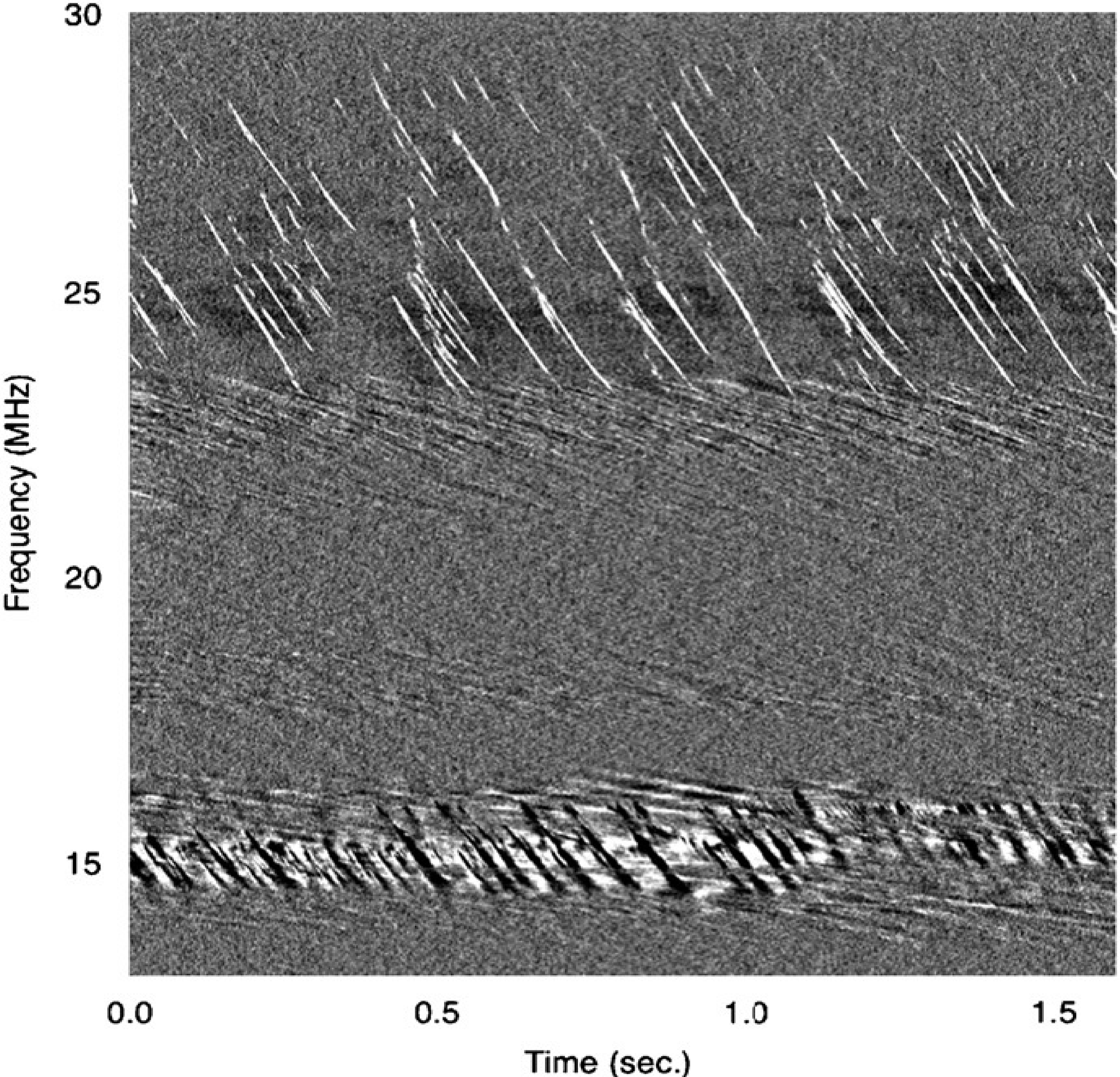
Potential Sources of Fast Radio Transients

1. Pulsars
   Giant pulses (coherent emission from
   sometimes a beach-ball size region <-- nanosecond)

2. RRATS

3. Radio flares from
   Brown dwarfs
   Jupiter
   Solar bursts
   Active stars
   AGN outbursts (Extra-galactic, higher frequencies)

4. Many other known and unknown ??! sources
   Recent reports on Fast Radio Bursts (FRBs)
   ... argued to be of extragalactic origin (large DMs) !



30
25
20
15
Frequency (MHz)
0.0
0.5
1.0
1.5
Time (sec.)

1. General considerations for optimum detection:

a) targeted search

b) blind search

might differ in size of the instantaneous field of view.

Common to both is Matched Filtering...

parameter space:

dispersion measure, pulse width/shape (and period)

Here, we focus on non-recurring fast transients, which are hard to catch, and even harder to confirm.

Fast transients: signal necessarily from
compact sources,
broad-band (also coherent
across BW = 1/temporal_width),
and most likely highly polarized

NOTE:
sensitivity increases LINEARLY within coherence bandwidth, which could be high here, unlike for steady radio noise

a) targeted search:

detection probability dp <-- sensitivity
<-- collecting area (A), bandwidth, pulse-width

as long as beam-size >= source-size, higher A and longer look --> higher dp

b) all-sky (blind) search:

detection probability

<-- sampled volume & look duration

<-- sensitivity,
field of view x N_beams,
look duration or duty-cycle

<-- collecting area (A), bandwidth,
pulse-width, look duration

b) all-sky (blind) search:

sensitivity <-- A;

probed-distance <-- sqrt(A)

sky coverage at any time <-- N_beams/A

probed volume <-- N_beams/sqrt(A)

The benefit of large A can be realized only with the correspondingly larger number of beams.

(Of course, relevant luminosity distribution of the targets of interest is also to be included).

These considerations assumed filled-apertures.

Dilute apertures have poorer
volume coverage for fast transients.

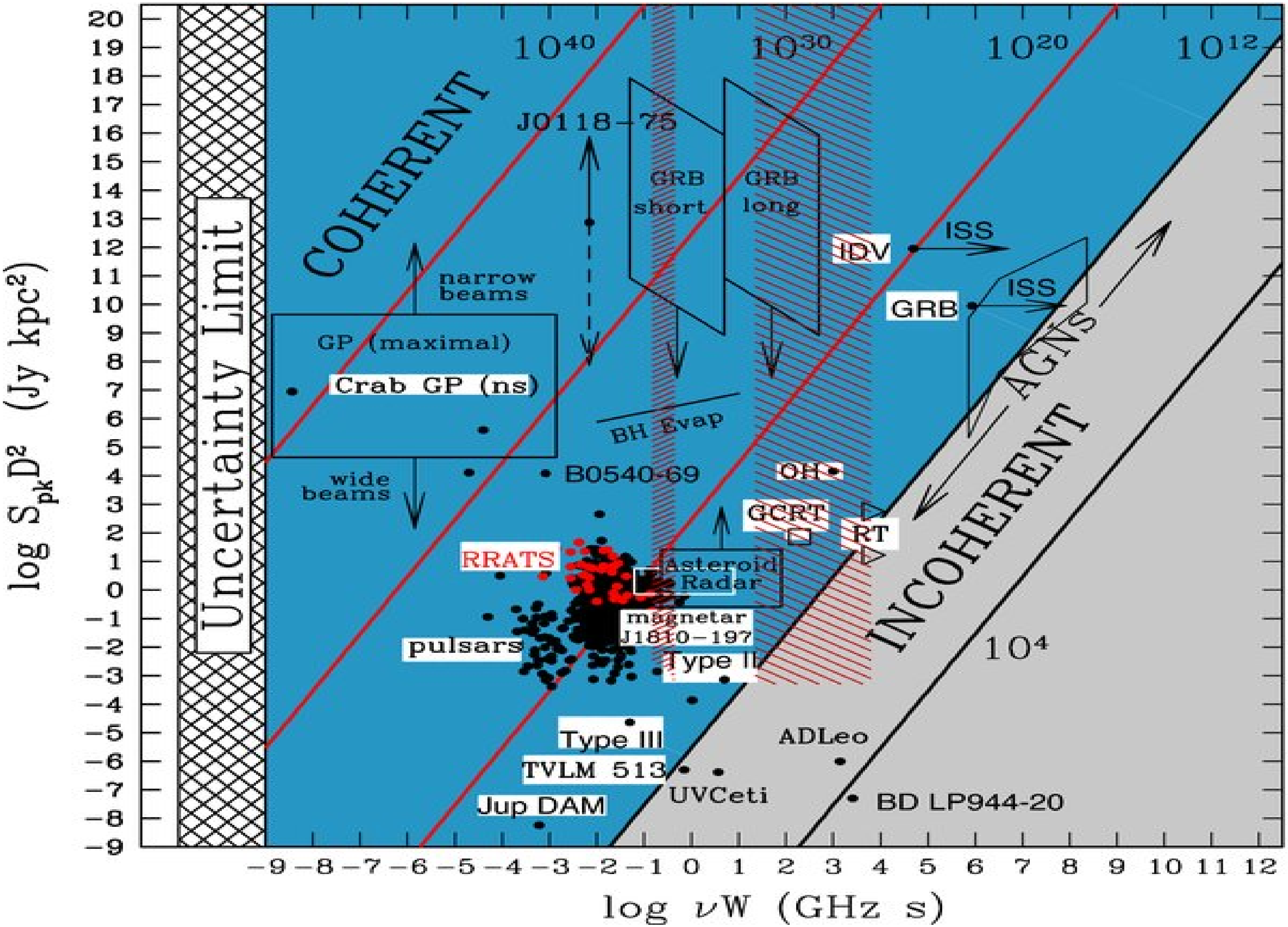
Use of multiple apertures to cover different directions appears more rewarding, compared to combining them
as an incoherent array....

....as far as “sampled volume” is concerned.

Bandwidths: for delta_f < BW_coh < BW,

sensitivity <-- sqrt(BW*BW_coh)

Cordes 2009



Uncertainty Limit
COHERENT
INCOHERENT
10^40
10^30
10^20
10^12
10^4
J0118−75
GRB short
GRB long
IDV
ISS
ISS
GRB
AGNS
narrow beams
wide beams
GP (maximal)
Crab GP (ns)
BH Evap
B0540-69
OH
GCRT
RT
RRATS
Asteroid Radar
magnetar J1810−197
pulsars
Type II
Type III
TVLM 513
Jup DAM
UVCeti
ADLeo
BD LP944-20
log $S_{pk}D^2$ (Jy kpc^2)
log νW (GHz s)

Bhat et al 2011

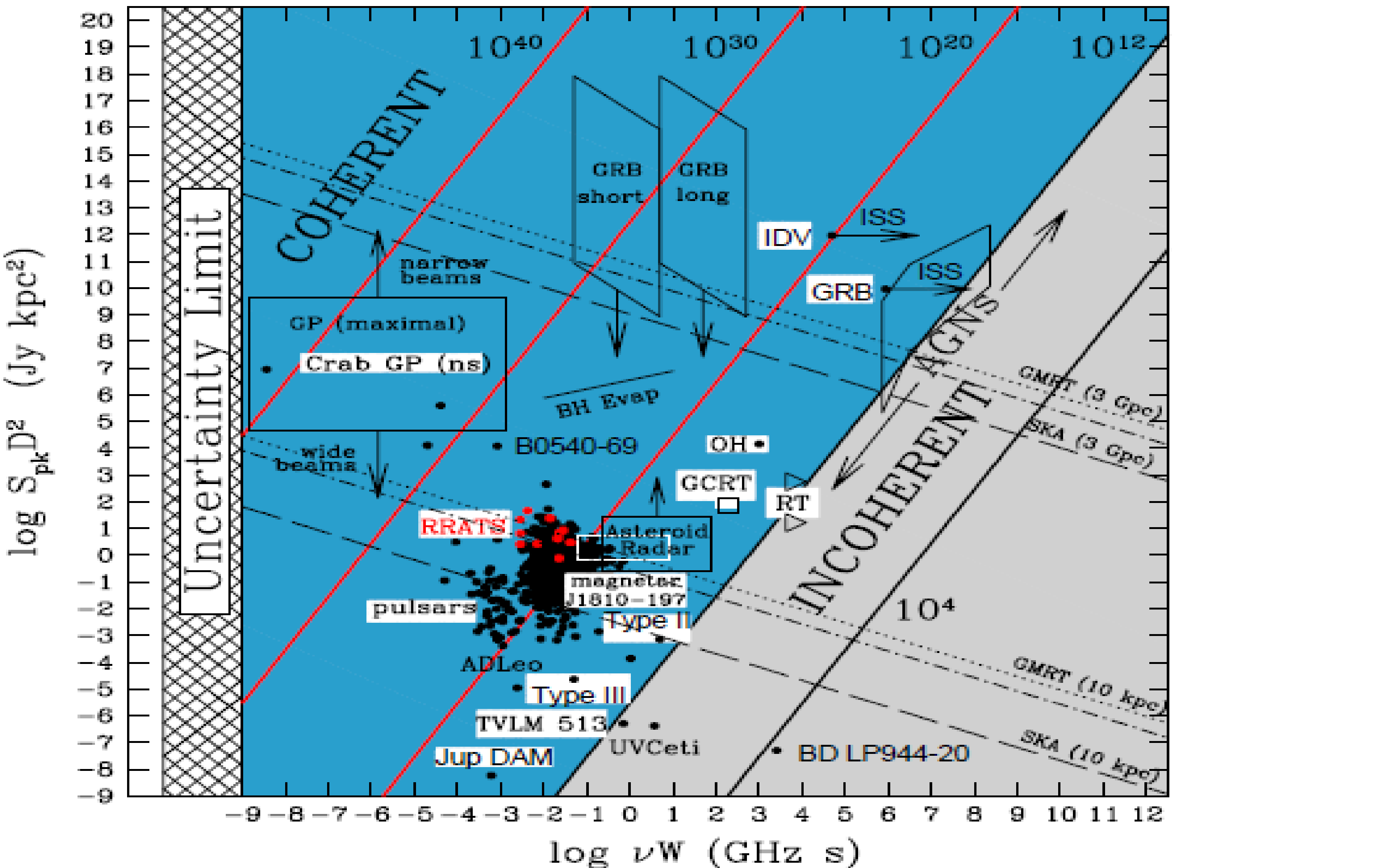


Figure 1. Time-luminosity phase space for known radio transients from Cordes (2009); a log–log plot of the product of peak flux density S_{pk} in Jy and the square of the distance D in kpc vs. the product of frequency ν in GHz and pulse width W in s. The uncertainty limit on the left indicates that $\nu W > 1$ as follows from the uncertainty principle. Lines of constant brightness temperature $T_b = SD^2/2k(\nu W)^2$ are shown, where k is Boltzmann's constant. Points are shown for the nano-giant pulses detected from the Crab, giant pulses detected from the Crab pulsar and a few millisecond pulsars, and single pulses from other pulsars. Points are shown for Jovian and solar bursts, flares from stars, brown dwarfs, OH masers, and AGNs. The regions labeled coherent and incoherent are separated by the canonical 10^{12} K limit from the inverse Compton effect that is relevant to incoherent synchrotron sources. The growing number of recent discoveries of transients illustrates the fact that empty regions of the νW–$S_{pk}D^2$ plane may be populated with sources not yet discovered. The figure also includes hypothetical transient sources and detection curves; e.g. maximal giantpulse emission from pulsars, prompt radio emission from GRBs, bursts from evaporating black holes, and radar signals used to track potentially impacting asteroids and comets in exosystems. Long-dashed lines indicate the detection threshold for the full SKA for sources at distances of 10 kpc and 3 Gpc. Dotted and dot-dashed lines correspond to the current and future GMRT at 1.2 GHz (i.e. bandwidths of 32 MHz and 400 MHz, respectively). At a given νW, a source must have luminosity above the line to be detectable. The curves assume optimal detection (matched filtering).

Using VLBA data in parallel

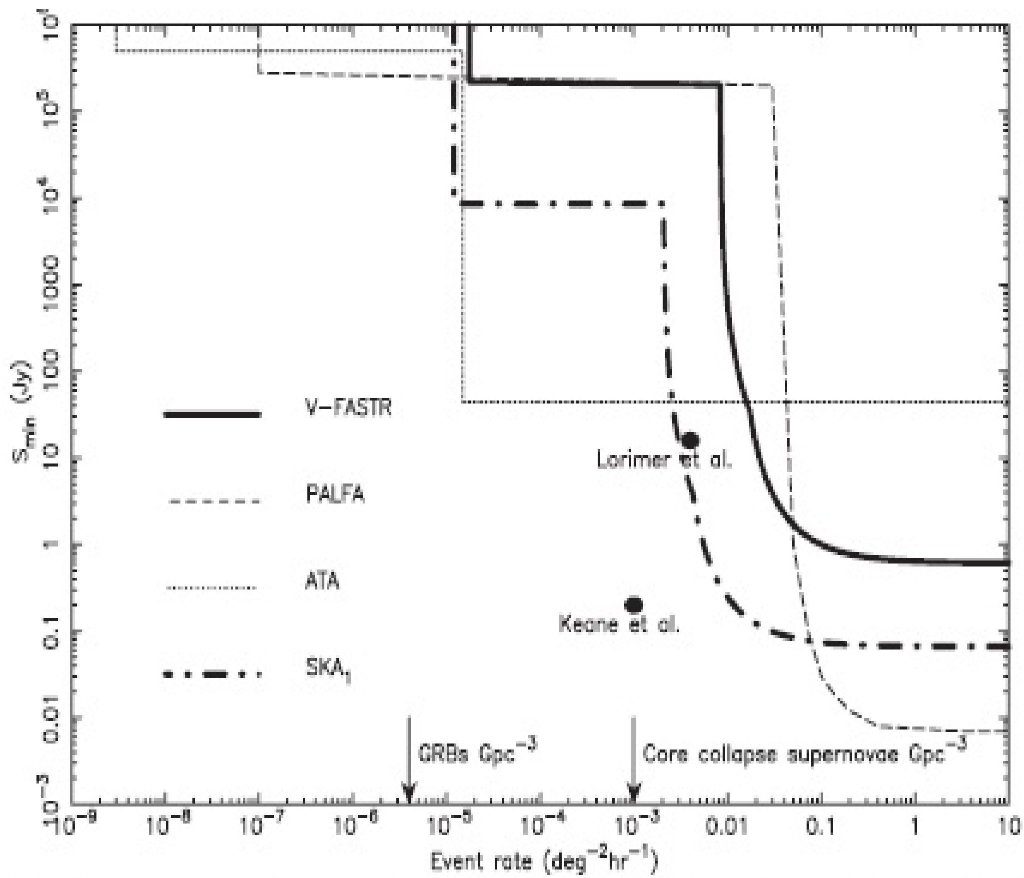
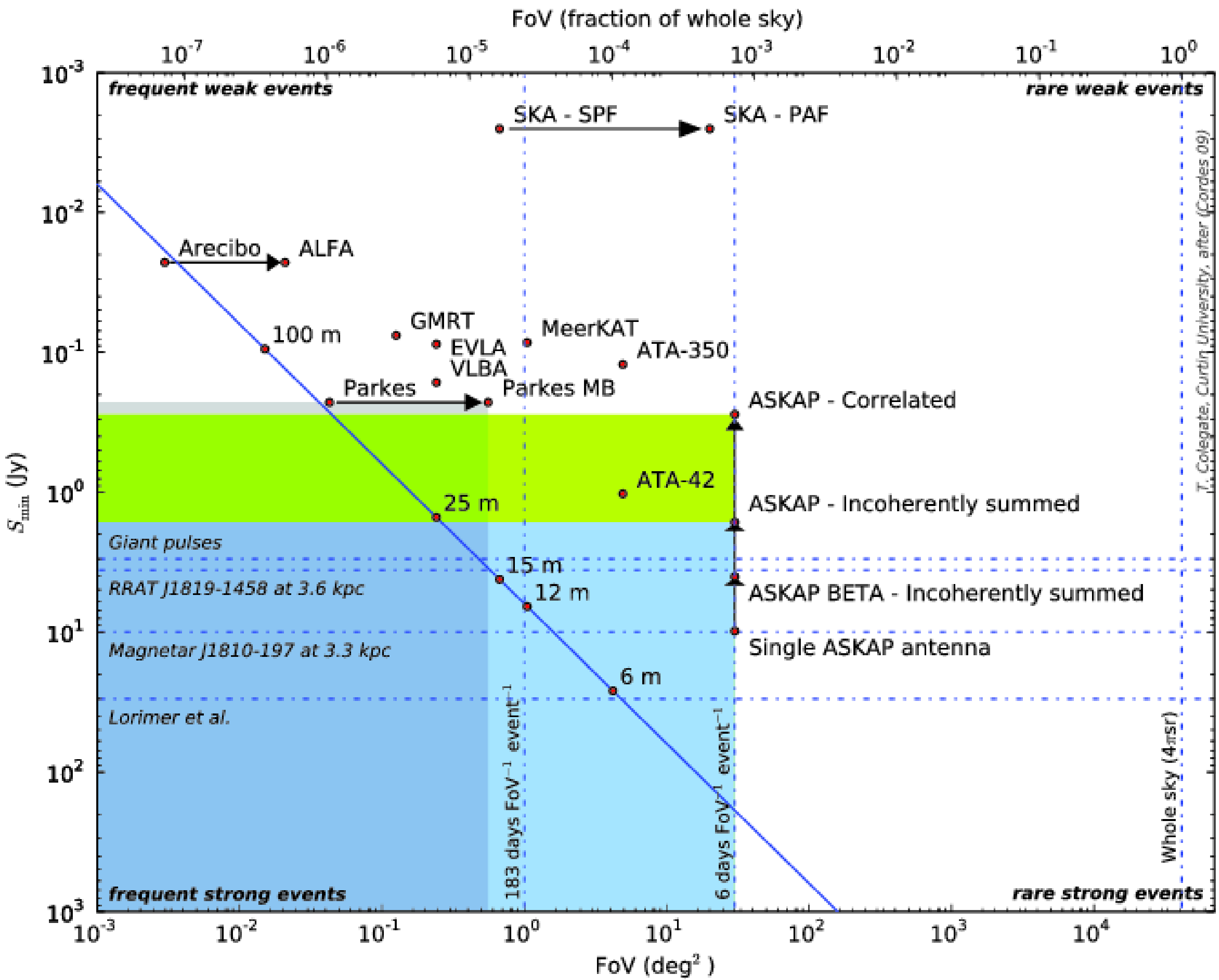


Figure 1. V-FASTR event rate limits (solid line) at 1.4 GHz compared to limits also at 1.4 GHz from Deneva et al. (2009) (dashed line) and Siemion et al. (20
(dotted line). The event rates inferred from the Lorimer and Keane bursts are shown, as are the event rates for GRBs and core-collapse supernovae used by Siemi
et al. (2012). Also shown are the event rate limits for the Phase 1 SKA dish array, as described in the text (dot-dashed line).

Table 1



FoV (fraction of whole sky)
frequent weak events
rare weak events
SKA - SPF
SKA - PAF
Arecibo
ALFA
100 m
GMRT
EVLA
VLBA
MeerKAT
ATA-350
Parkes
Parkes MB
ASKAP - Correlated
ATA-42
25 m
ASKAP - Incoherently summed
Giant pulses
15 m
RRAT J1819-1458 at 3.6 kpc
12 m
ASKAP BETA - Incoherently summed
Single ASKAP antenna
Magnetar J1810-197 at 3.3 kpc
6 m
Lorimer et al.
183 days FoV^{-1} event^{-1}
6 days FoV^{-1} event^{-1}
Whole sky (4πsr)
frequent strong events
rare strong events
T. Colegate, Curtin University, after (Cordes 09)
S_{min} (Jy)
FoV (deg^2)

Radio Frequency Interference (RFI) Detection & Mitigation

First order detection/mitigation happens naturally

i.e. Broadband RFI show up at 0.0 DM-value

Identify deviations from the otherwise smooth spectrum as narroband RFI
.. and exclude such spectral channels

Monitor ratio of the expected to the observed standard deviation of intensity variation in each of the channels; RFI will show a dip

Radio Frequency Interference (RFI) Detection & Mitigation

Can antennas filter pre-specified RFI bands ?

Yes.

Can polarization filter be used, i.e. Can Removal of polarized component help ?

No.
Risky !... since your transient signal
Is likely to be polarized.

How to ensure immunity to RFI ?

Go to remote places free of RFI ? e.g. MWA.
... but no escape from satellite signals
.... Moon reflects man-made RFI

Use of multiple locations.

How to ensure immunity to RFI ?

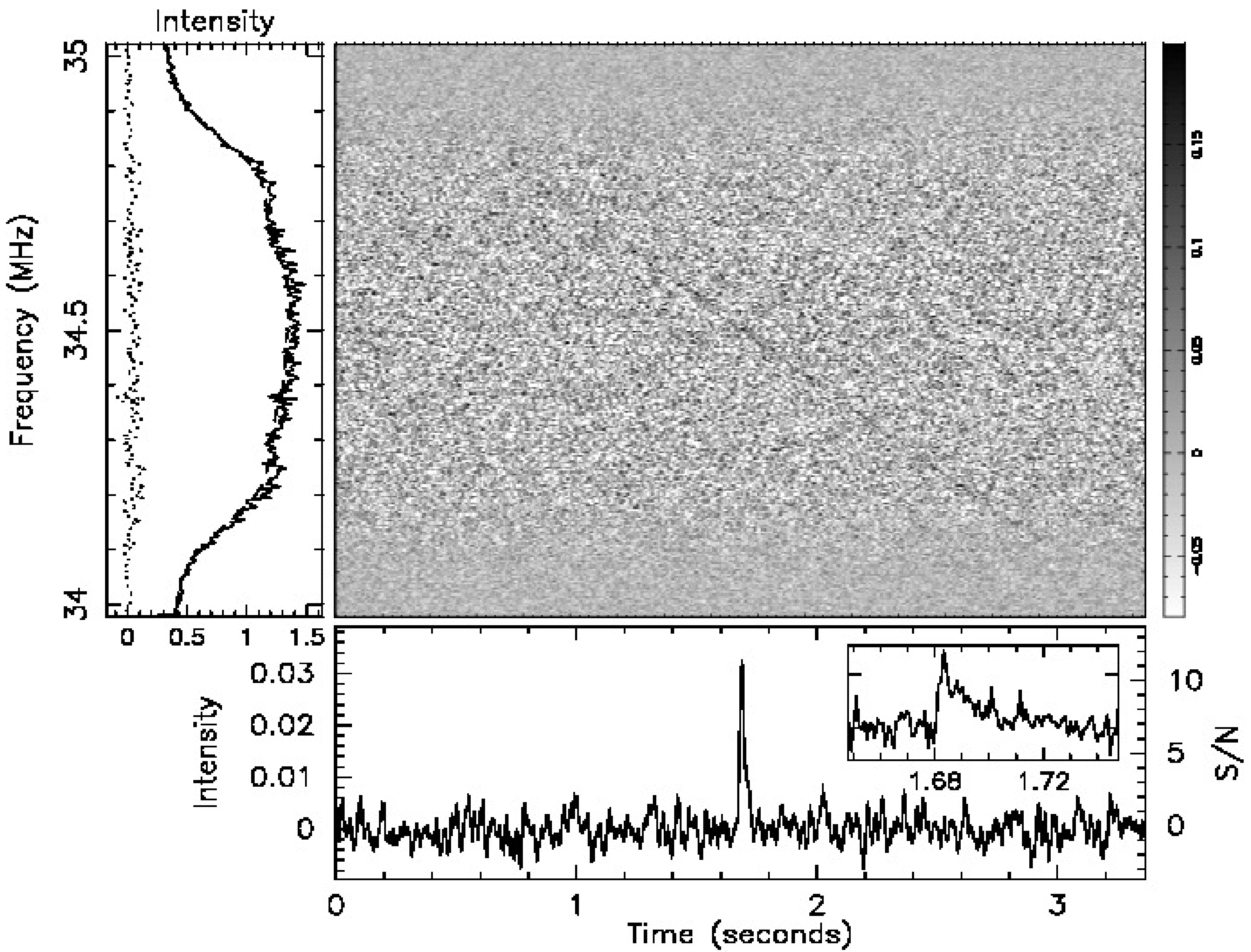
Appeal to large span in frequency,
or rather span in wavelength-square..
to exploit the dispersion characteristics
of the sky signal.

Even the expected frequency dependence can be checked for, i.e. F^-2, as a criterion.

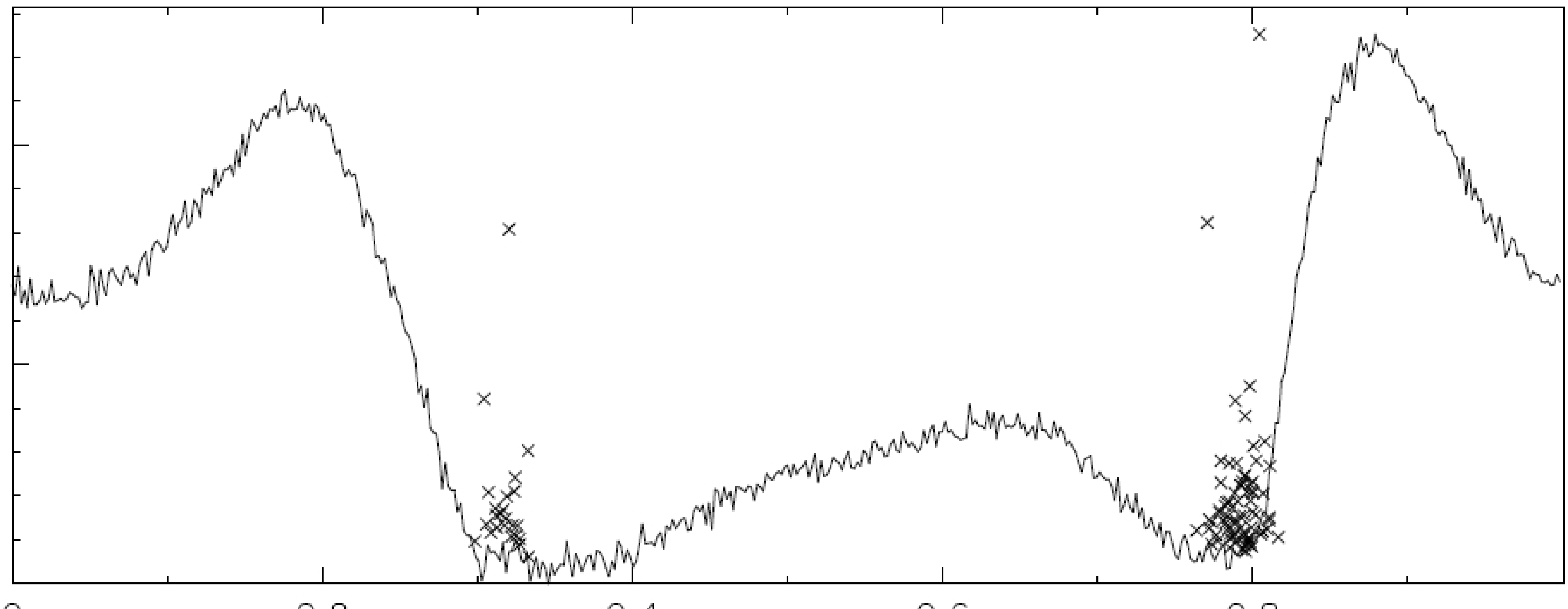
2. Single-pulse searches: a case-study with data from the Gauribidanur telescope (IIA+RRI; Freq. 34.5 MHz; 12000 sq m)

.....A possible detection of a radio counterpart of a Fermi-LAT pulsar (Yogesh Maan, Aswathappa,+ 2012)

and more...



Intensity
35
34.5
34
Frequency (MHz)
0
0.5
1
1.5
0.03
0.02
0.01
0
Intensity
1.68
1.72
10
5
0
S/N
0
1
2
3
Time (seconds)

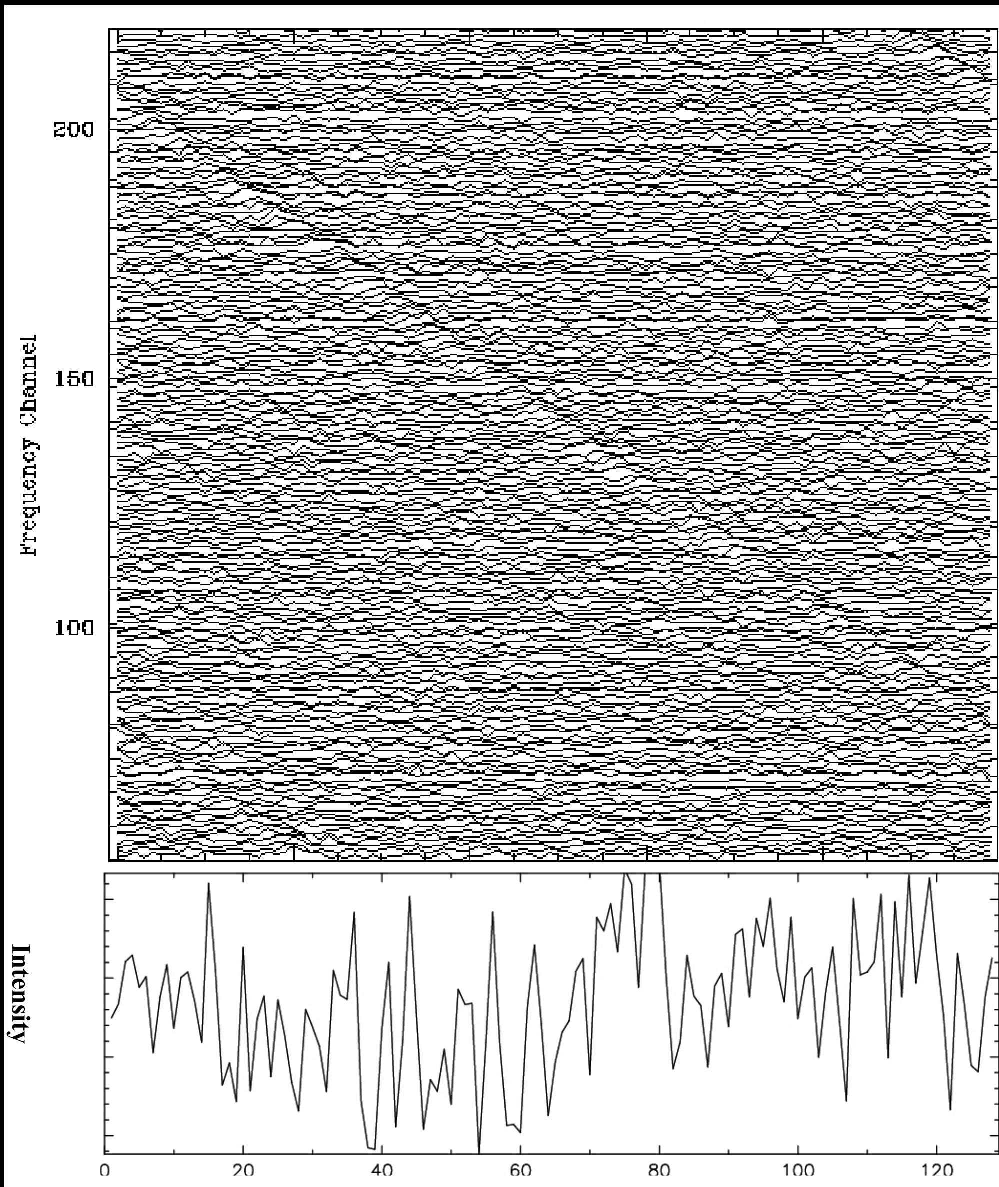


0
0.2
0.4
0.6
0.8

Single-pulse detection

- Single pulse search technique: Methodology:
    1. Dedispersion at a range of DMs
    2. Matched-filtering for different pulse widths
    3. Thresholding for significance assessment
    4. Diagnostics
- Radio Frequency Interference : Detection & mitigation

Effects of Dispersion and its Correction

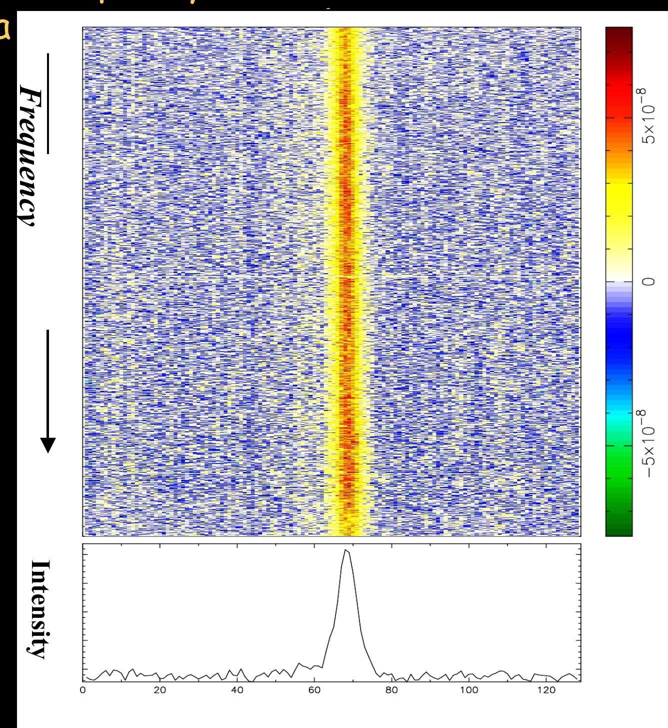


ν = 1420 MHz, $\Delta\nu$ = 32 MHz

Δt/DM << 1 msec ;

ν = 35 MHz, $\Delta\nu$ = 1 MHz,
Δt/DM ~ 200 msec ;

- **Incoherent (Post-detection) dedispersion:** Signal time sequence from each frequency channel is shifted backwards by a



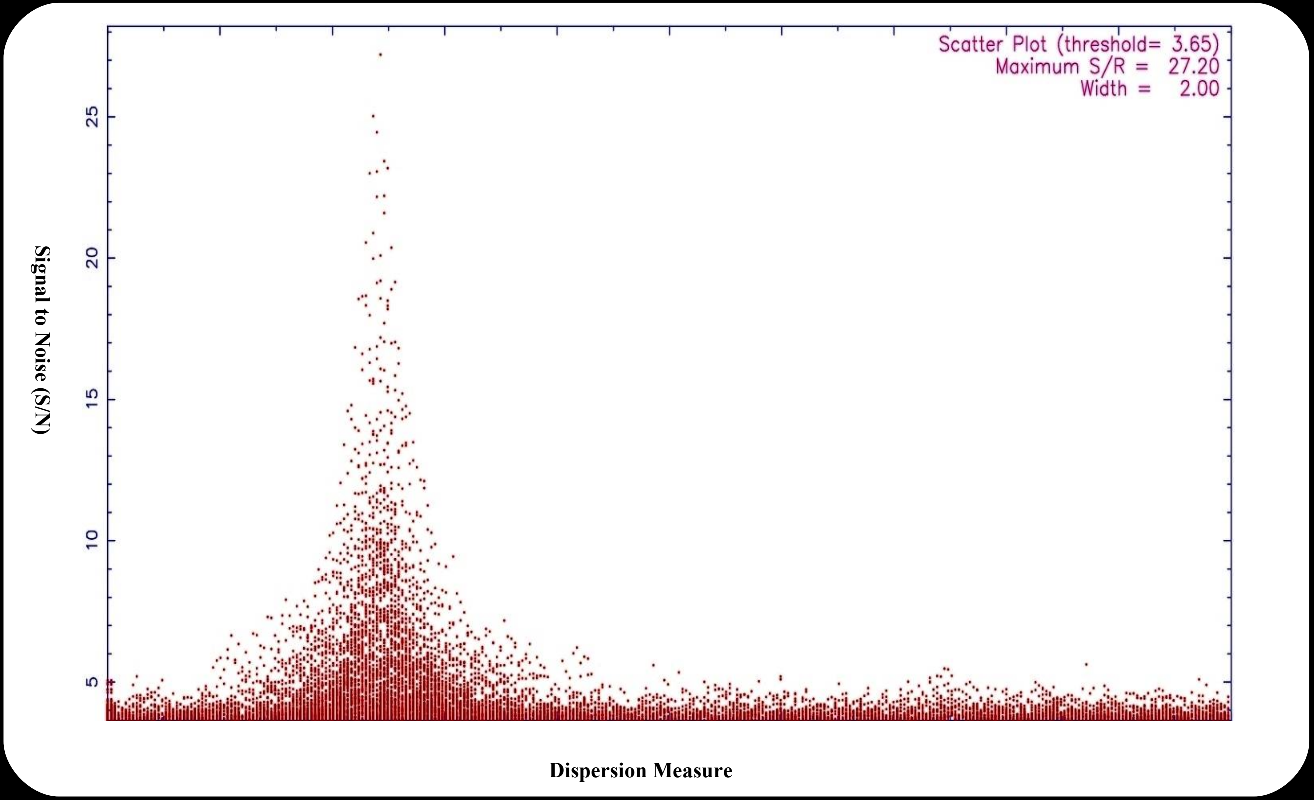
Spacing of DM-values

Δ DM $\propto f^3/\Delta f$

$\propto \Delta t$

Example detection by dedispersing over a trial DM-value range

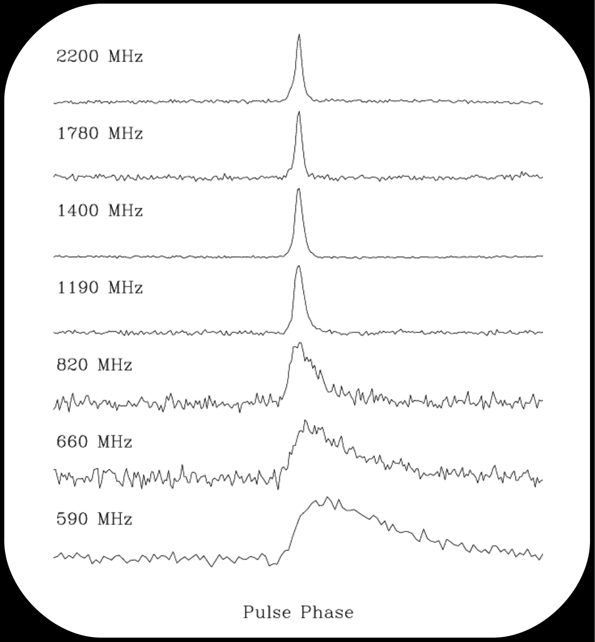
Data taken from observations in the direction of pulsar B1133+16



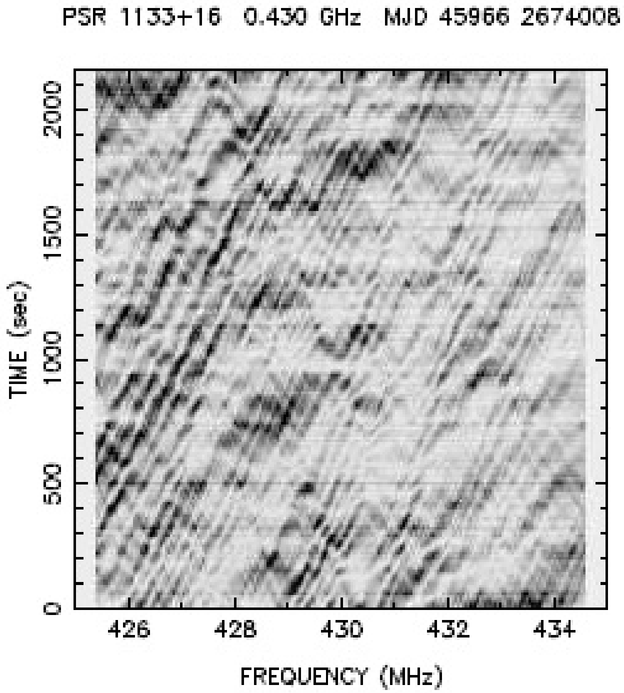
Matched Filtering

Smoothing time = width of the pulse
=> Maximum Signal to noise Ratio

Most Dominant Factor which decides the Pulse-Width at 35 MHz : Interstellar Scattering



- Convolution of the intrinsic pulse with a one-sided exponential function
- Scattering time-scale ~ $f^{-4} \times DM^2$



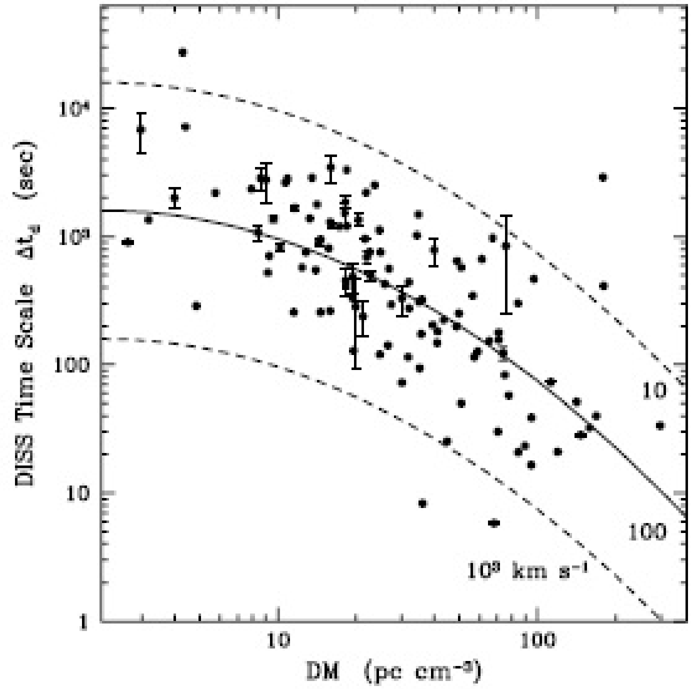
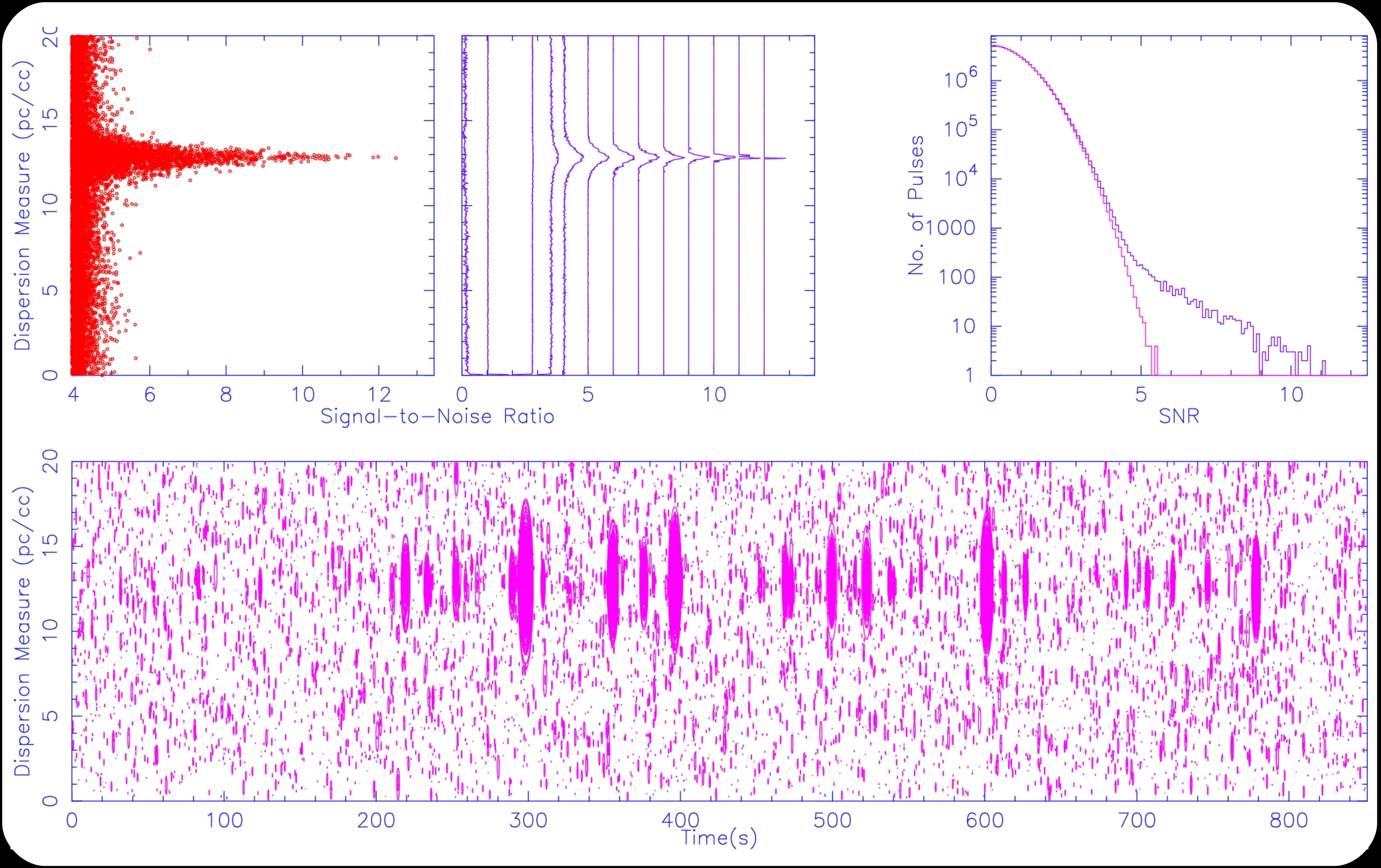


FIG. 1.— Left: Dynamic spectrum of pulsar B1133+16 at 0.43 GHz, showing diffractive ISS with 100% modulations (i.e. rms / mean) of the pulsed flux. The characteristic time and frequency scales are very strong functions of frequency and of the particular scattering along the line of sight to the pulsar.

FIG. 2.— Right: The characteristic DISS timescale at 1 GHz plotted against DM for a sample of pulsars. For objects with multiple observations, the vertical bars designate the $\pm 1\sigma$ variation of the mean value. The solid and dashed lines show predicted DISS timescales for transverse source velocities of 10, 100 and 10^3 km s^{-1} using results discussed in Cordes & McLaughlin (2004). The DISS timescale varies with frequency as $\Delta t_{\rm d} \propto \nu^{1.2}$ if the scintillation bandwidth has the Kolmogorov scaling, $\Delta\nu_{\rm d} \propto \nu^{4.4}$, as appears consistent for some objects. For extragalactic sources, the DISS time scale will differ because the geometry of the scattering medium consists of a foreground region from the Galaxy and another region corresponding to material in the host galaxy (if any). Nonetheless, the order of magnitiude value of the time scale can be estimated using the value of DM expected from just the foreground material in the Galaxy. The points are from Bhat et al. (1999); Bogdanov et al. (2002); Camilo & Nice (1995); Cordes (1986); Dewey et al. (1988); Foster et al. (1991); Fruchter et al. (1988); Gothoskar & Gupta (2000); Johnston et al. (1998); NiCastro et al. (2001); and Phillips & Clegg (1992).

B0834+06



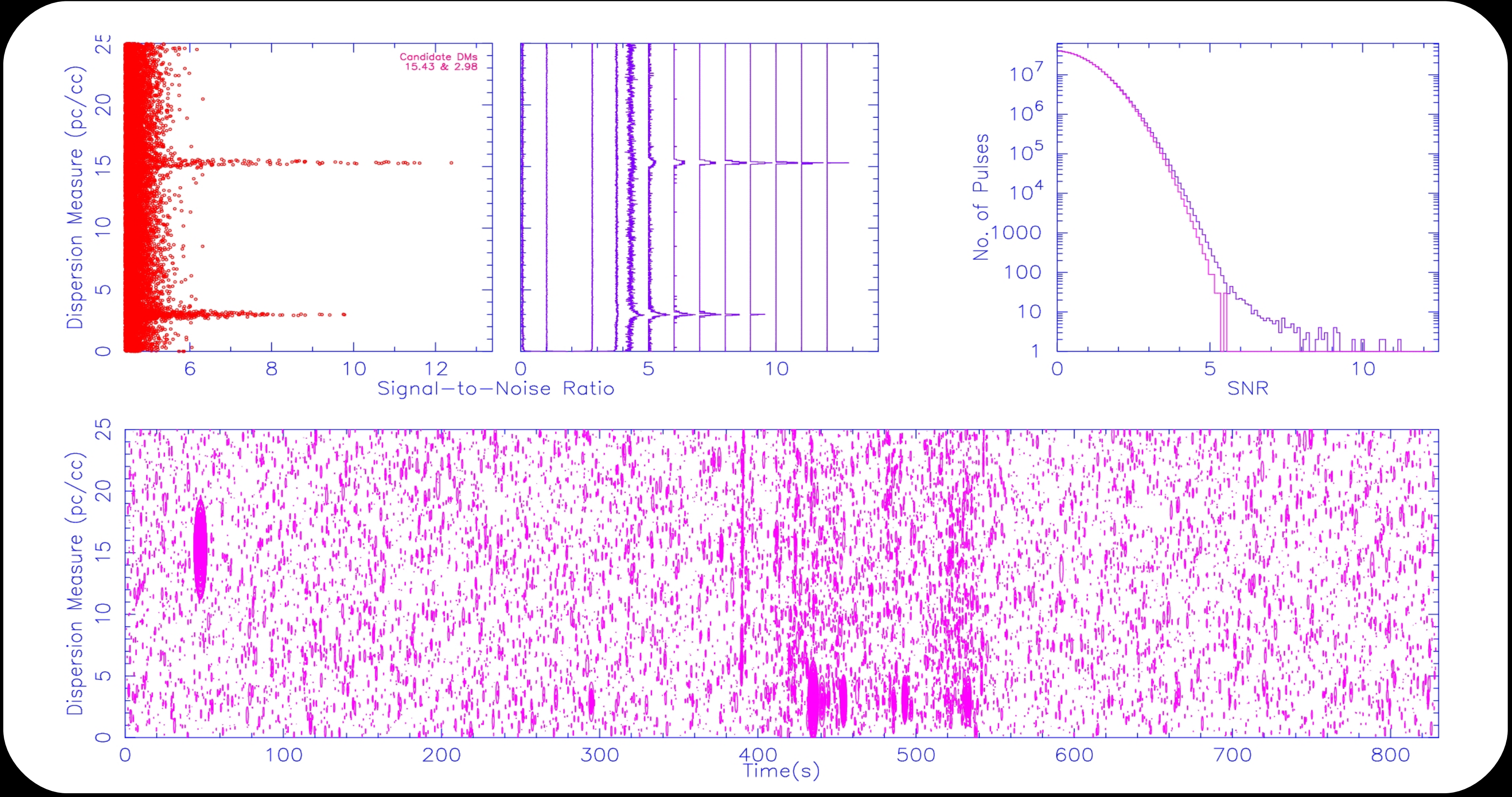
Dispersion Measure (pc/cc)
Signal—to—Noise Ratio
No. of Pulses
SNR
Dispersion Measure (pc/cc)
Time(s)

2. Sensitivity

Periodicity search needs a number of pulses present in the data to be searched

SPS is sensitive to even a single bright pulse, even if buried in RFI.

More than one transient sources present in the beam can be detected simultaneously (using MST-Radar antenna)

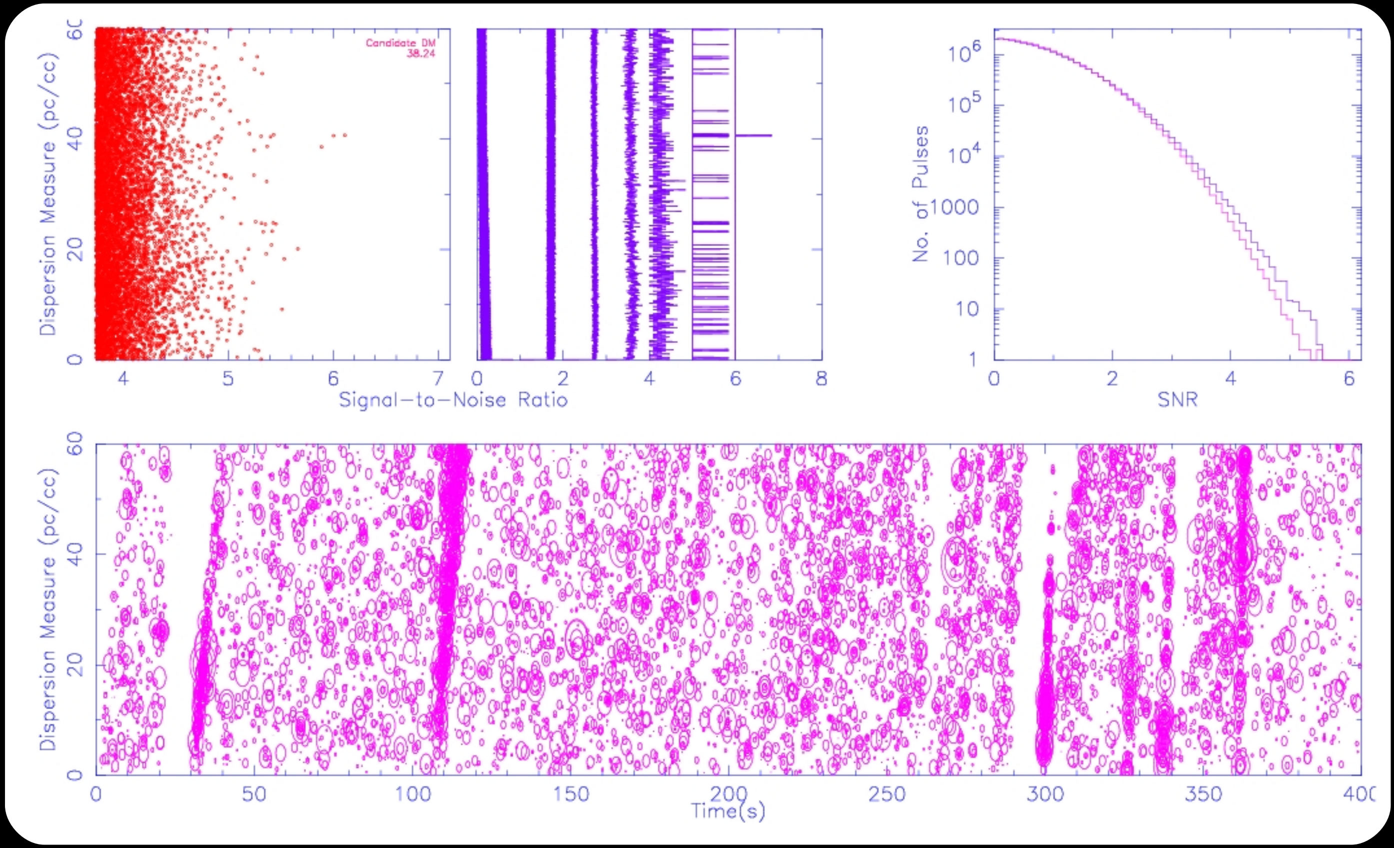


Narrow-band RFI

- Remove the corresponding frequency channels

Broad-band RFI

- Problematic for low-DM signals



- part of data can be removed => Low sensitivity

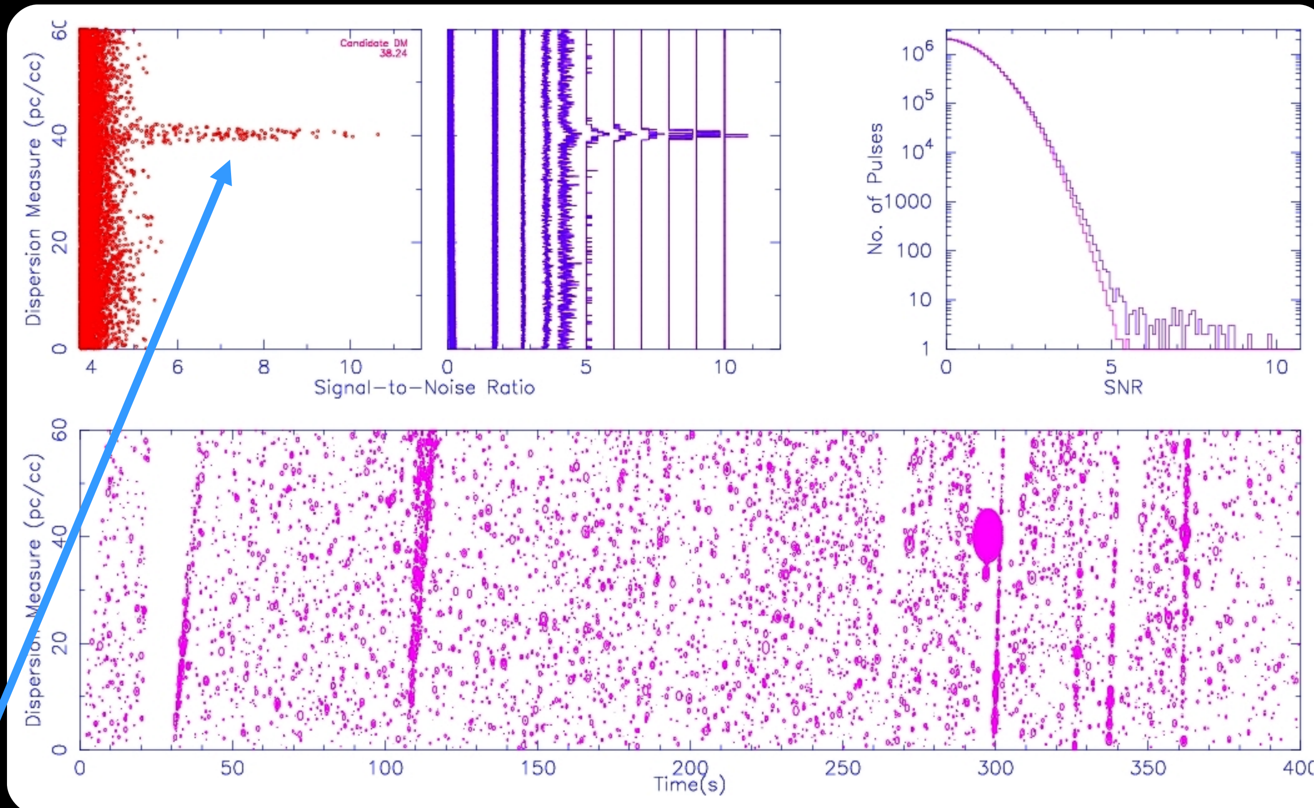
Is that enough ?

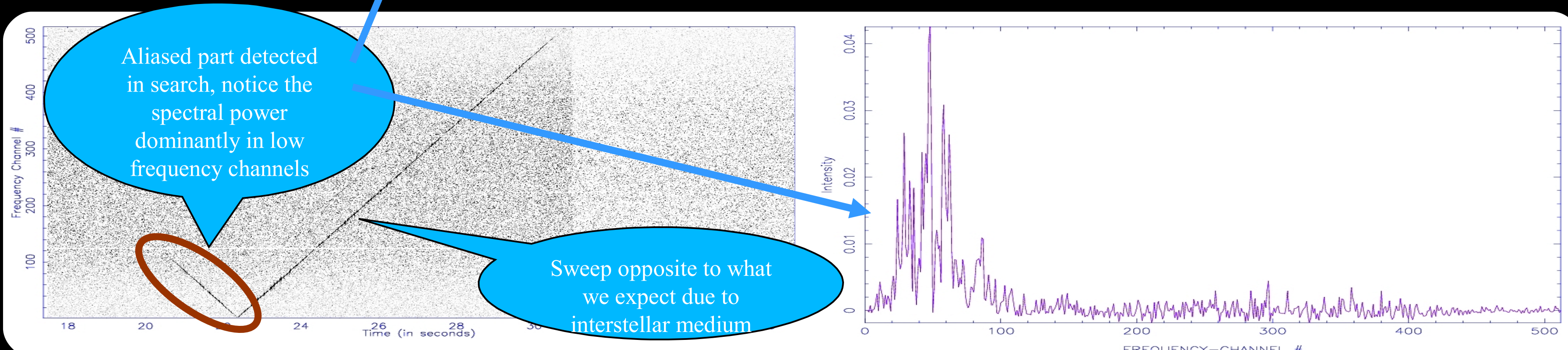
Very difficult for any RFI to mimic the distinct dispersive characteristics at low frequencies

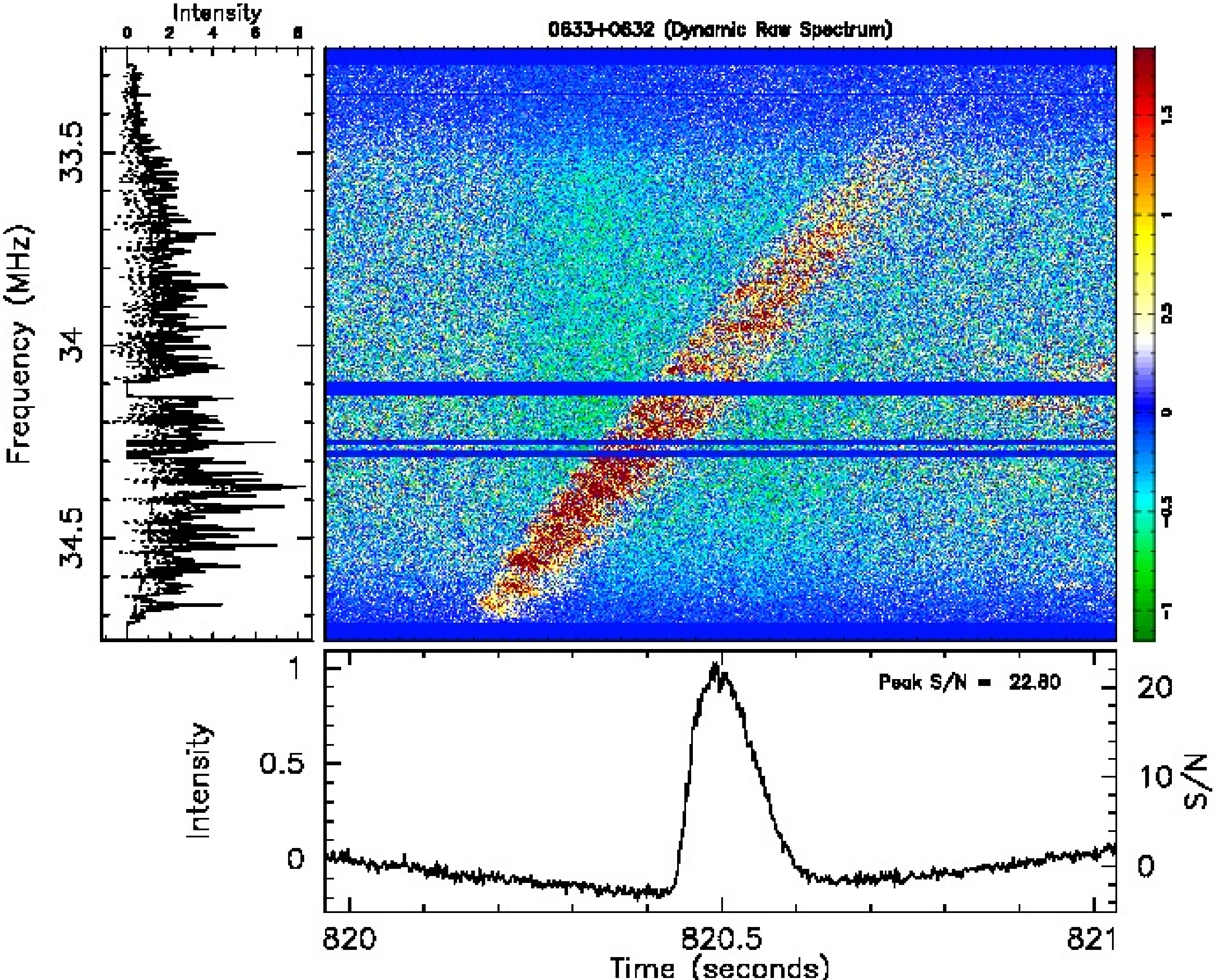
(Δt/DM (pc/cc) ~ 212 ms at 35 MHz, Δf=1 MHz)

Swept-freq Radar ?

Needed further investigation






0633+0632 (Dynamic Raw Spectrum)
Intensity
0
2
4
6
8
Frequency (MHz)
33.5
34
34.5
1.5
1
0.5
0
-0.5
-1
Peak S/N = 22.80
Intensity
1
0.5
0
S/N
20
10
0
820
820.5
821
Time (seconds)

High Time Resolution at the MWA

This capability is relatively new within the MWA project
Currently under development

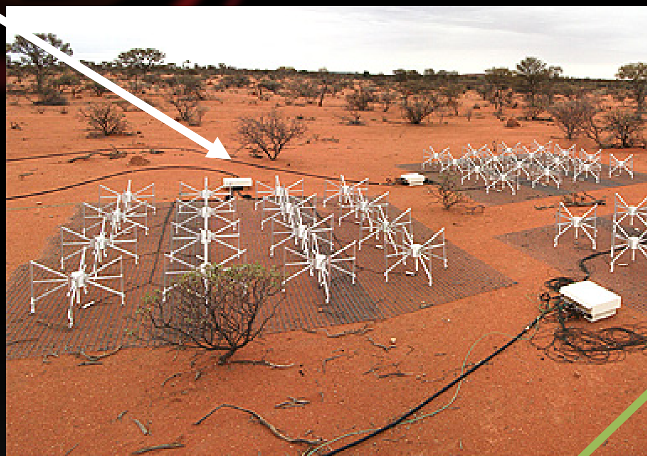
- MWA Correlator generates visibilities at 0.5 sec, 10 kHz resolutions

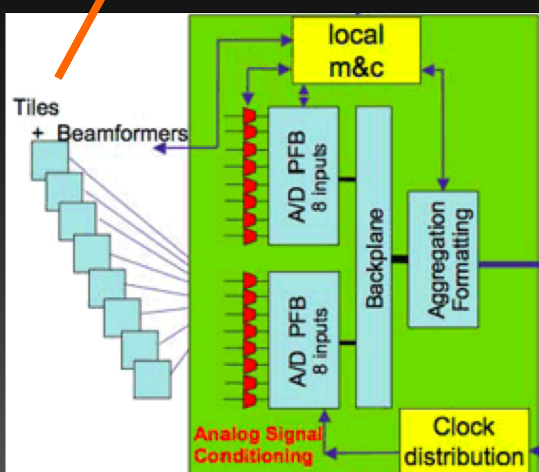
- High Time Resolution recorder (Voltage capture system + beam former + processing) is being designed to cater to science applications that require higher time resolution
    - (Solar, Pulsars, Fast Transients, etc.)

- Two related systems (eventually):
    - Transient detection system (TARDIS)
    - Full-bandwidth digital beam former (by RRI group)

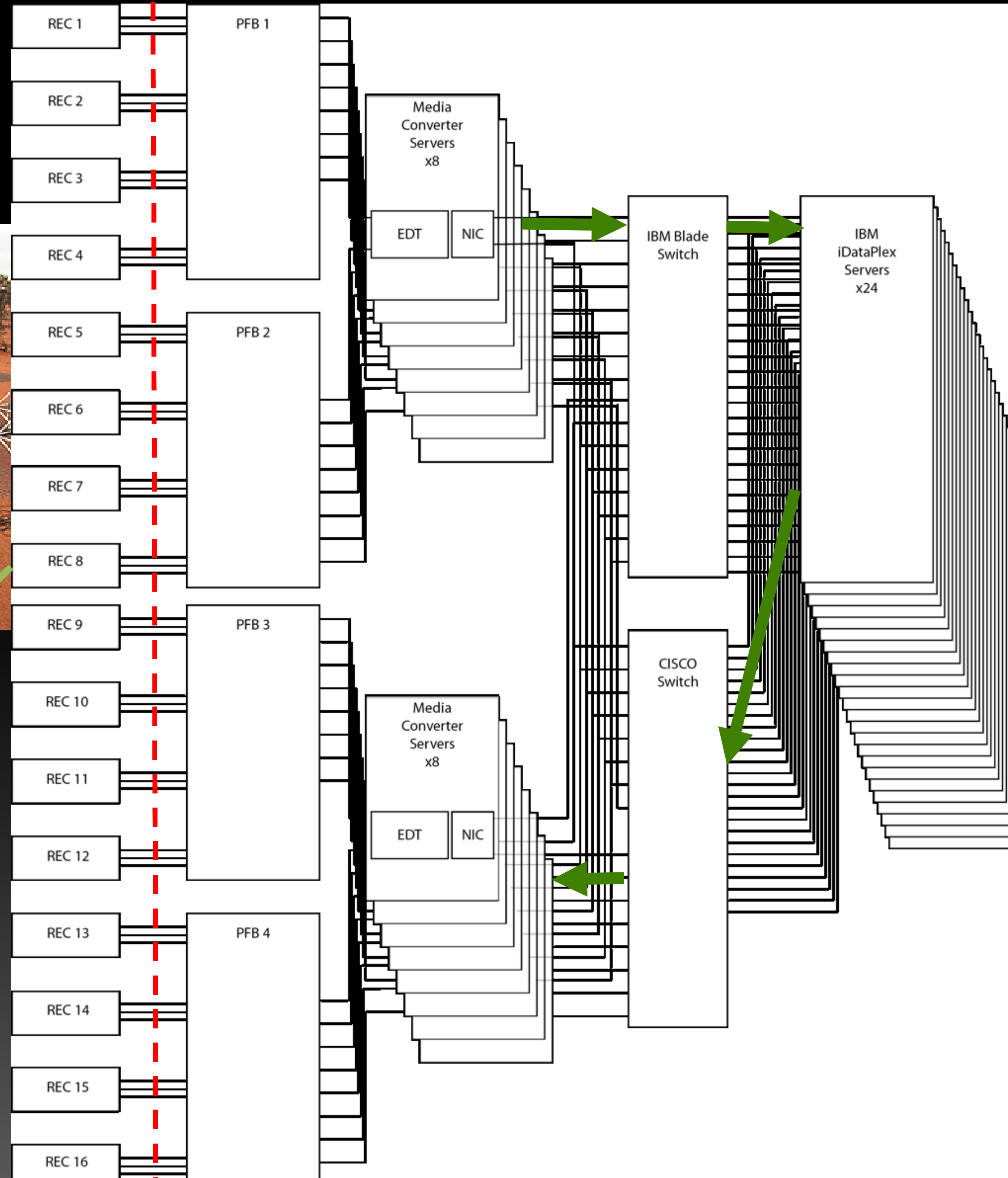
Beamformer

Tile (4 x 4 dipole array)





Receiver (for 8 Tiles)



MWA Correlator (128 Tiles, 3072 channels)

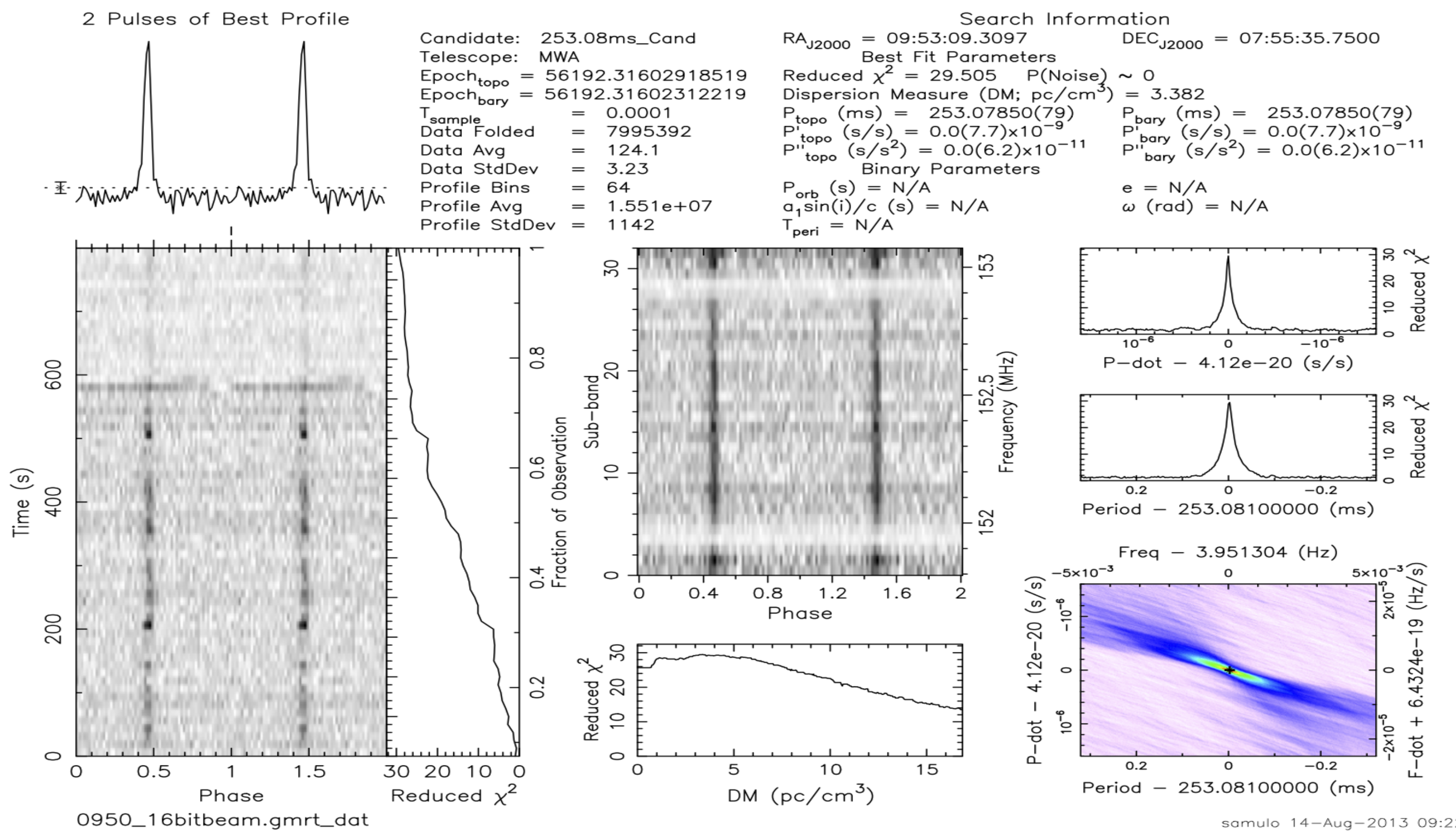
3. MWA related development

MWA:

128 tiles (16 dual pol elements each)
...total area comparable to the Parkes dish...
80-330 MHz sampled, but only 32 MHz BW is used/recorded at a time.

RRI's proposal for a full-band mode
... involves phasing of 8-tiles at the station level, and send out the full band with this partial phased-array mode, instead of 32 MHz from each tile.

Recent observations at MWA 128T: 12x1.28 MHz



Arecibo related development

Arecibo: GALFACTS

L-band, seven pixels, 300-MHz BW,

spectral-resolution -> 1 MHz

time resolution 1 msec.

Full Stokes

Meridian nodding mode, basket-weaving

Summary

- In Blind search : collecting area advantage is retained through use of multiple beams
- Coherence in spectra domain --> gain linear with BW_coh
- Benefits at Low-frequencies and/or with large spectral span
- Multiple stations crucial
- Exciting times ahead !
- Thank you for listening.