Matthew Bailes + HITRUN team.

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. Champion,[9] P. Coster,[2,3] N. D'Amico,[7,10] 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]

Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts' properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and intergalactic medium models suggest that they have cosmological redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident r- or gamma-ray signature was identified in association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

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CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS


MANCHESTER
1824


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SWIN
BUR
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SWINBURNE
UNIVERSITY OF
TECHNOLOGY


Curtin University


ICRAR


OAC
Osservatorio
Astronomico
di Cagliari


CSIRO


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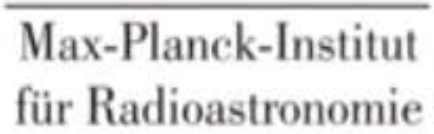
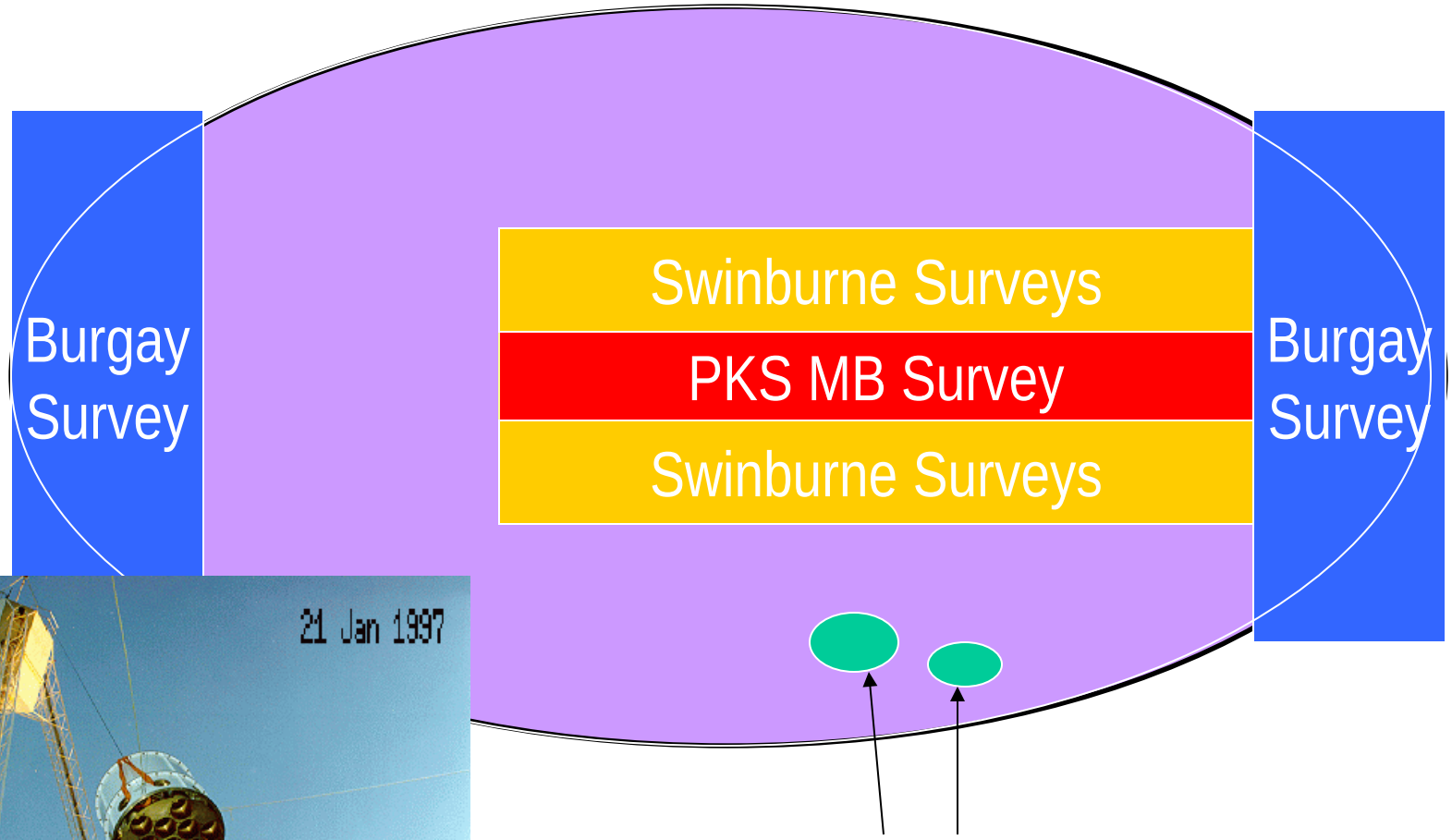
FOR ALL-SKY ASTROPHYSICS

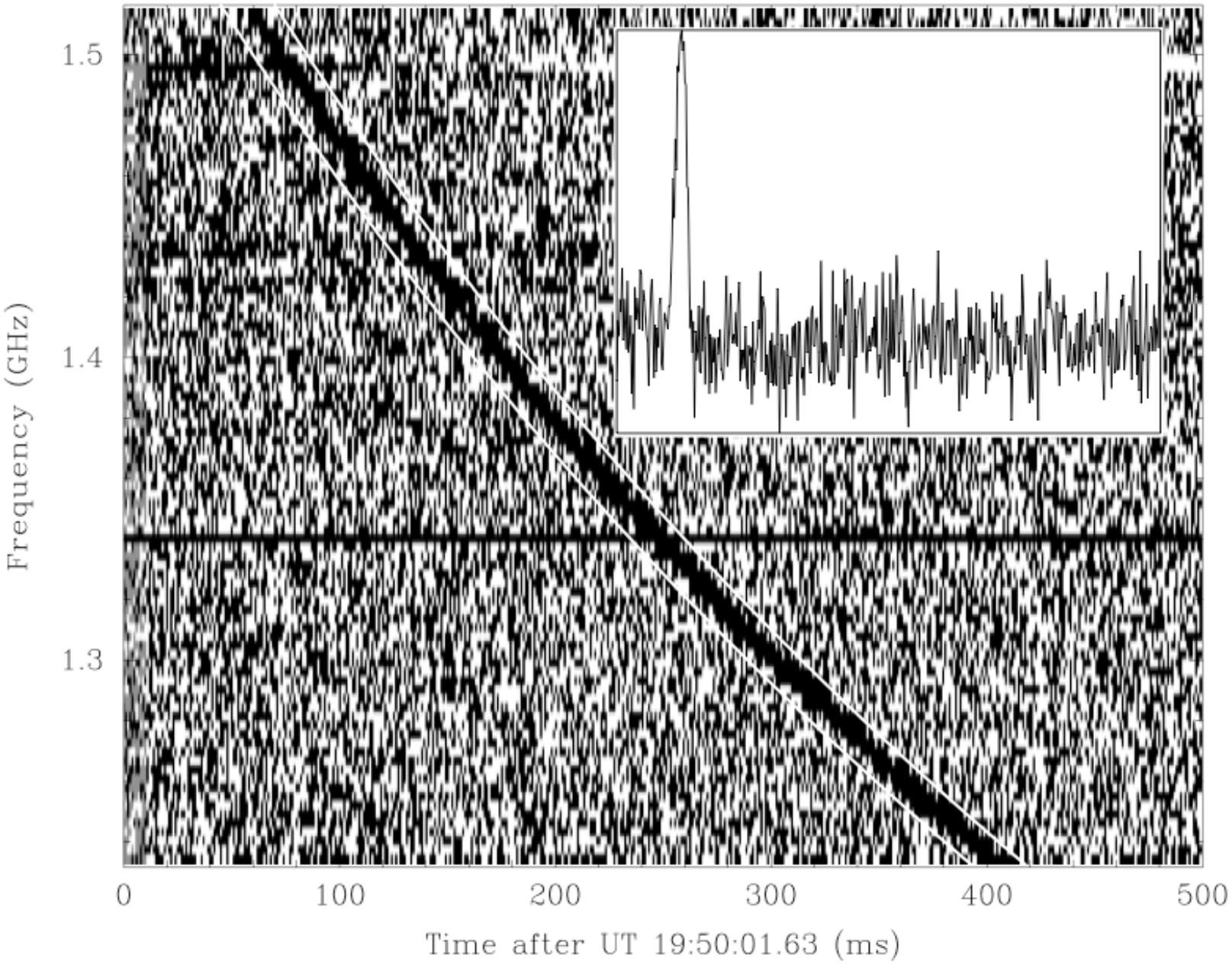

JPL
Jet Propulsion Laboratory
California Institute of Technology

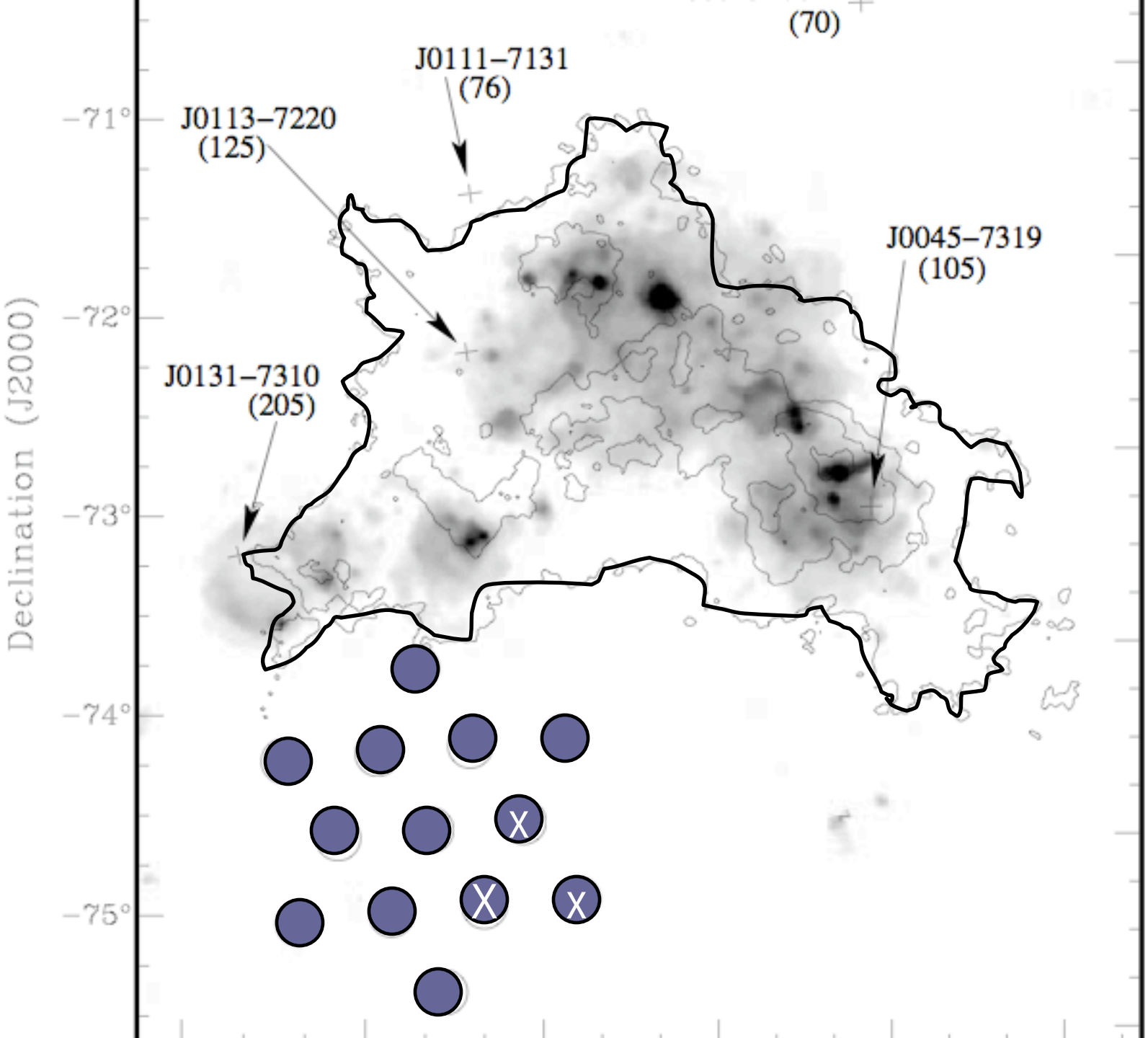

Max-Planck-Institut
für Radioastronomie

One-bit Parkes Pulsar Surveys (schematic galactic coords)



LORIMER BURST (2001 data, published in Lorimer et al. 2007)




(70)
J0111−7131
(76)
J0113−7220
(125)
J0045−7319
(105)
J0131−7310
(205)
−71°
−72°
−73°
−74°
−75°
Declination (J2000)

Lorimer Burst Puzzles

- Ridiculously Bright?
  - ~150 Jy-ms!!!
  - Implied 225 Lorimer Bursts/Day?
  - N 15 Jy-ms -> $10^{3/2}$ 225 = 10,000 day^{-1} ?
  - None seen.
- The “Perytons”
  - Seen at Parkes, similar DMs, RFI, Lightning?
  - Slightly fatter, Not always nicely curved.
- Ridiculously Luminous?
  - No known source population.

(2007 final slide) If we find more:

- They're definitely real!

- Sub-arcsec position from VLBI
  - "Host Galaxy" Redshift Determination
  - Integrated baryonic content of the Universe
    - ~100% ionised
- Many VLBI events
  - Baryonic density of the Universe(Z)

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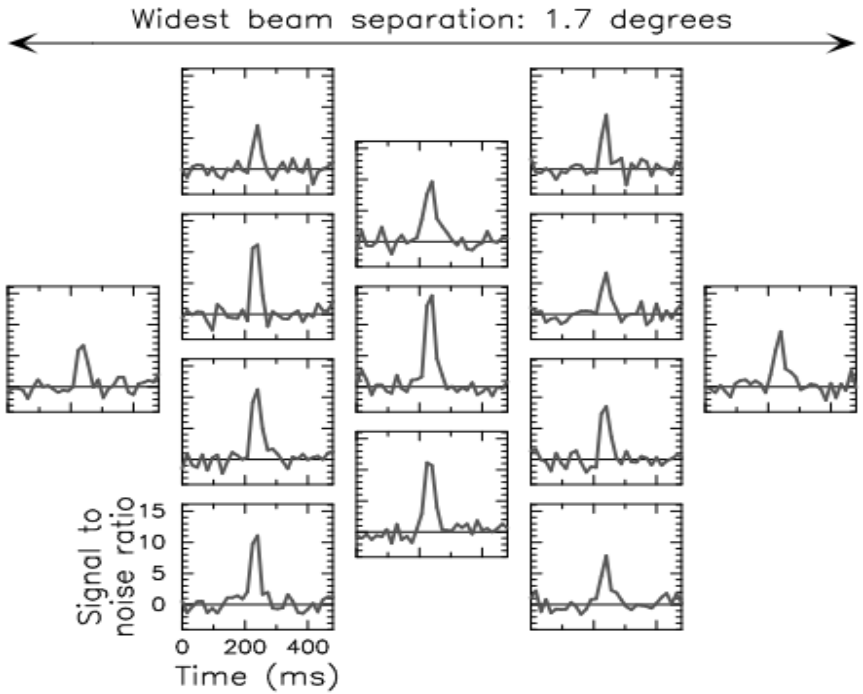
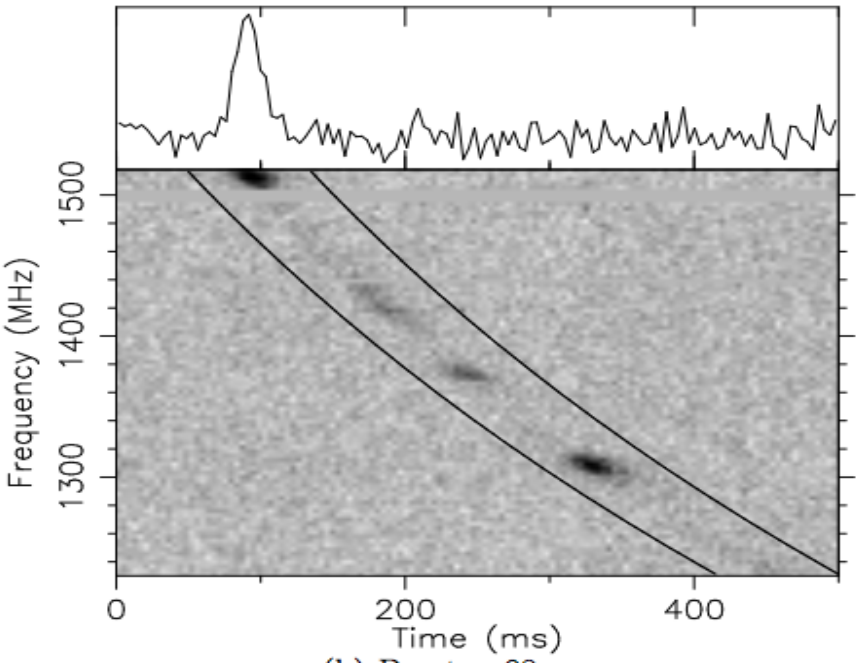
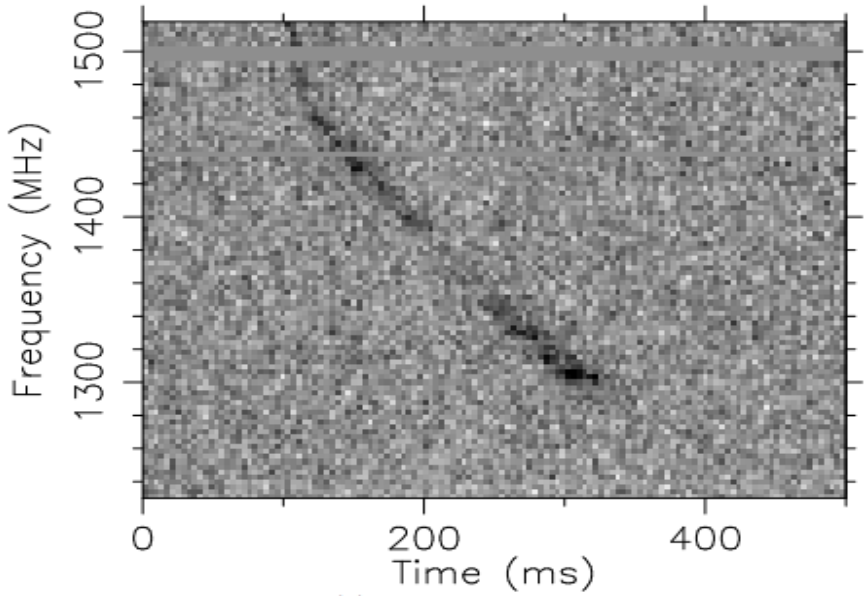


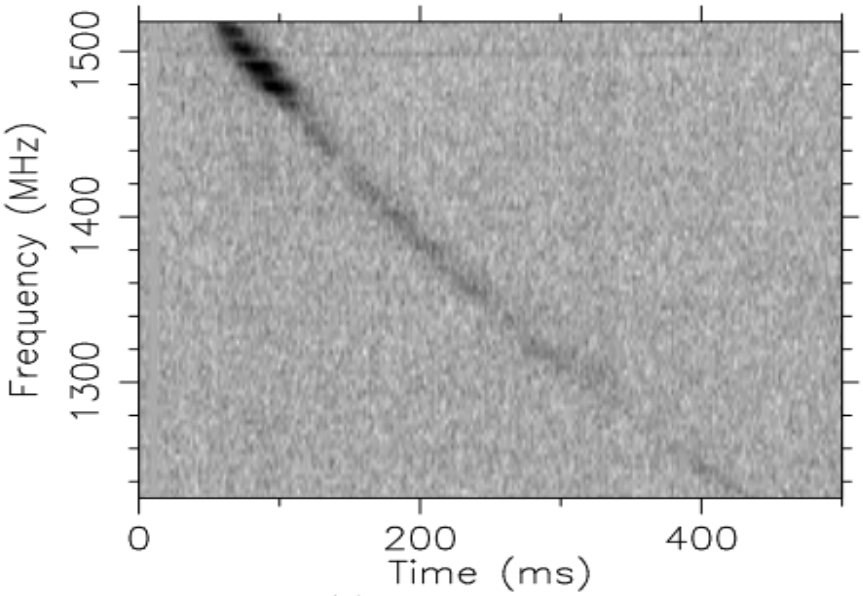
(a) Peryton 08 in 13 beams



(b) Peryton 08

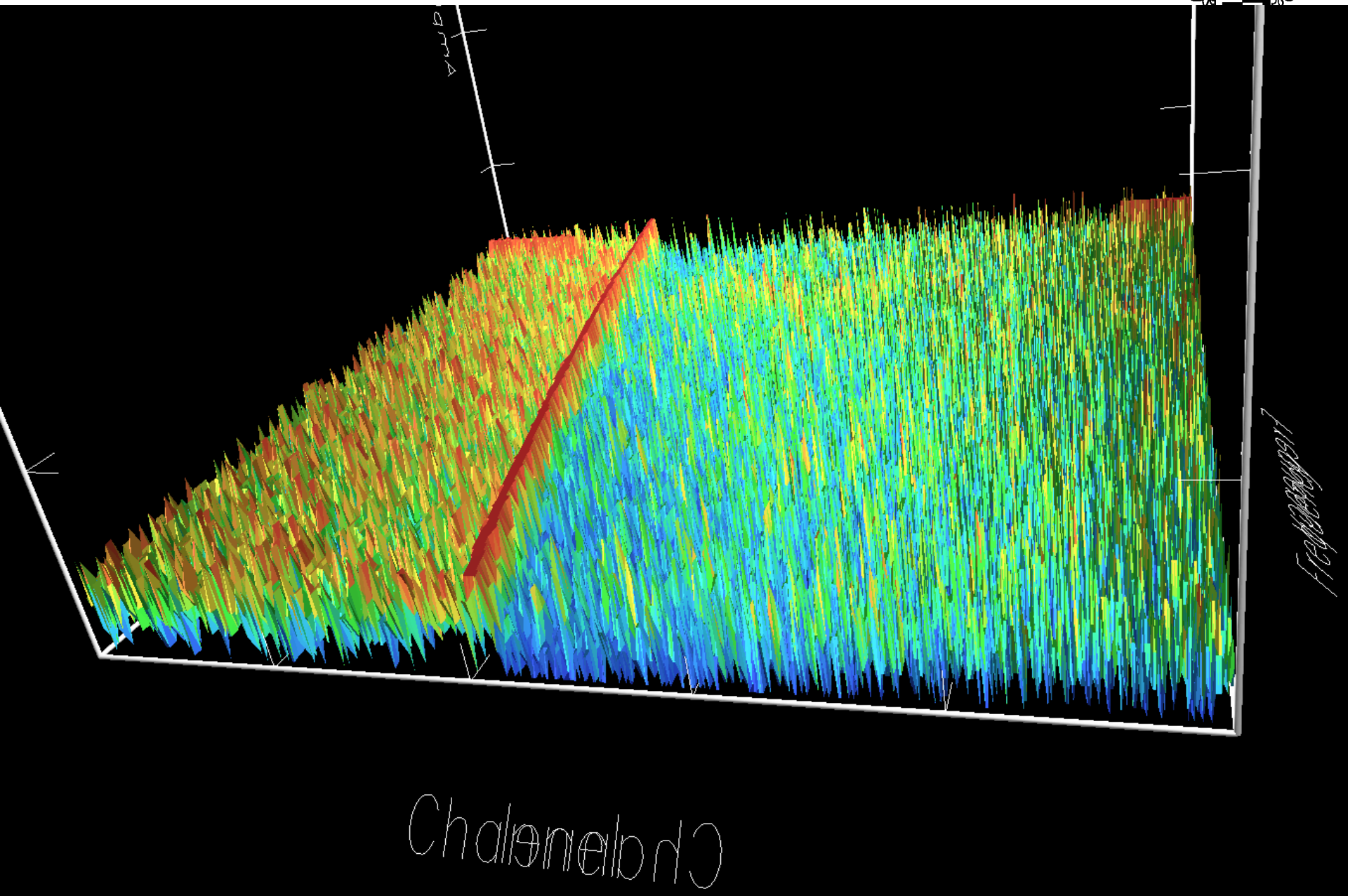


(c) Peryton 06



(d) Peryton 15

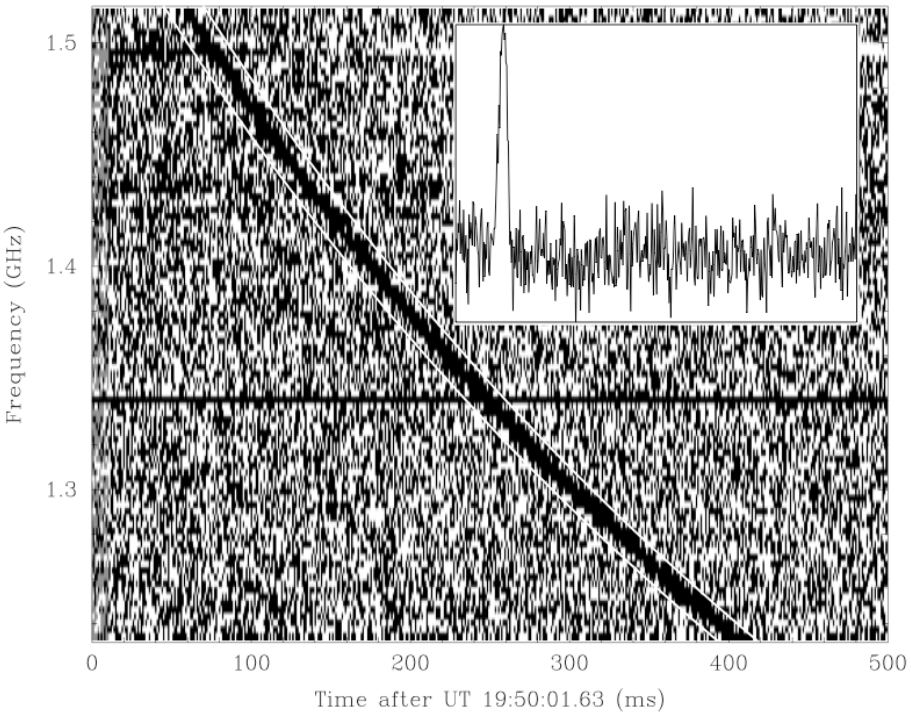
Old 1-bit Hardware



HITRUN Pulsar Surveys (Keith et al. 2010)

- Digital Versions of the Parkes MB Surveys
- 13 x 1024 x 64 us
  - Medium-Latitude Survey (540s)
  - Ultra-deep Survey (4000s)
  - All-sky Survey (260s)
- Better for high-DM MSPs
- Better for Lorimer bursts
- Better for RRATs
- Deeper than old surveys

1 Petabyte of Data!



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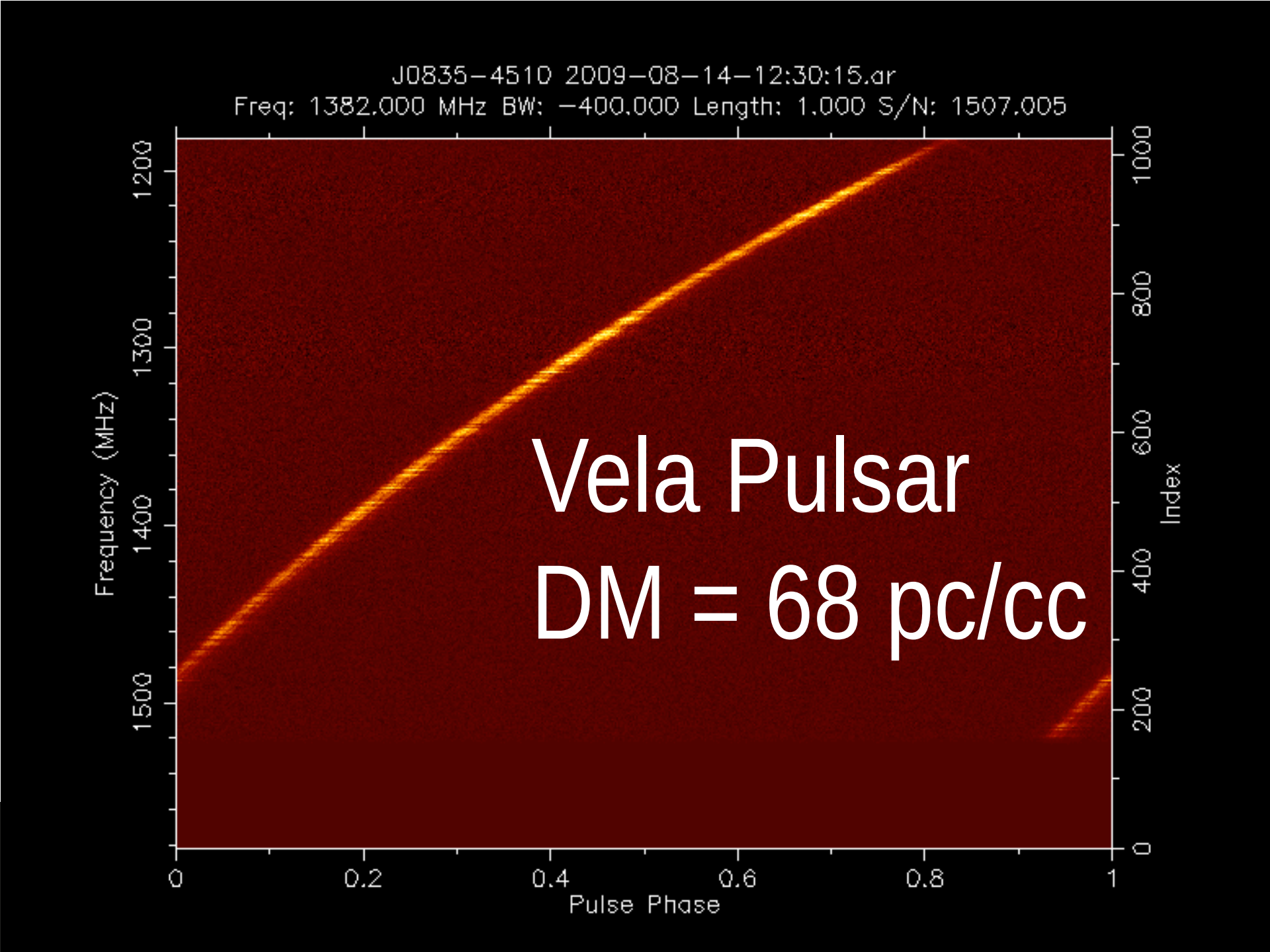
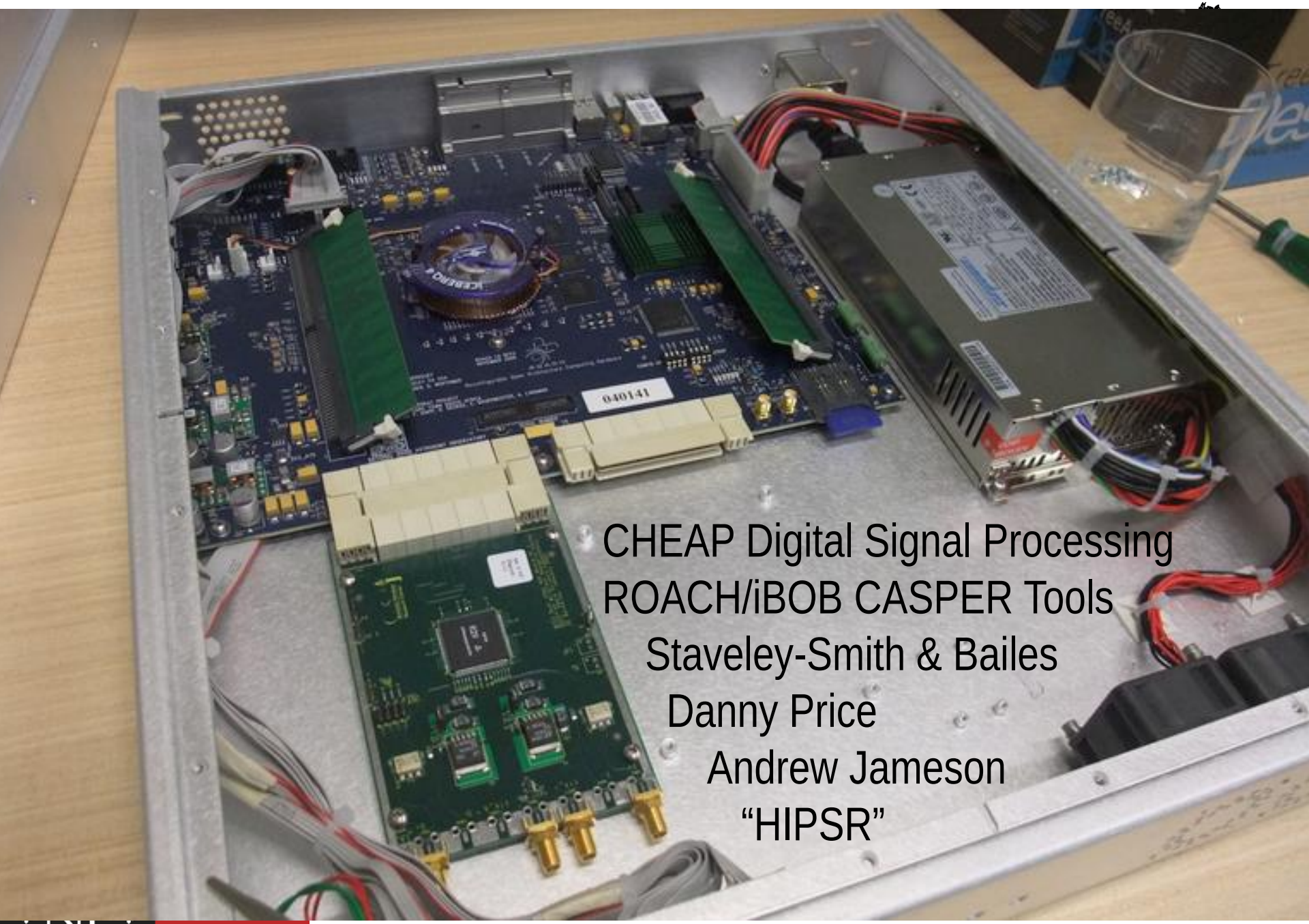
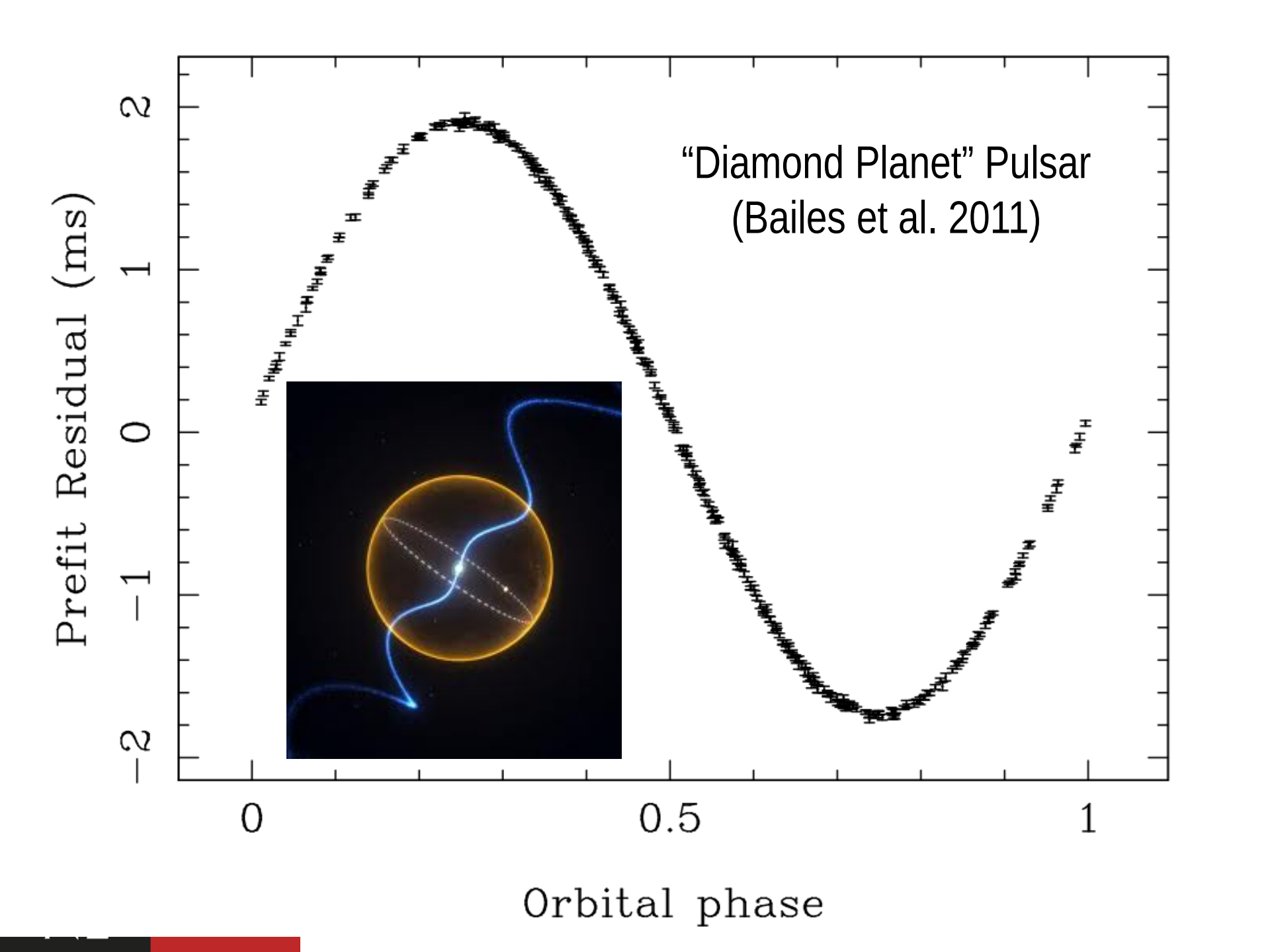
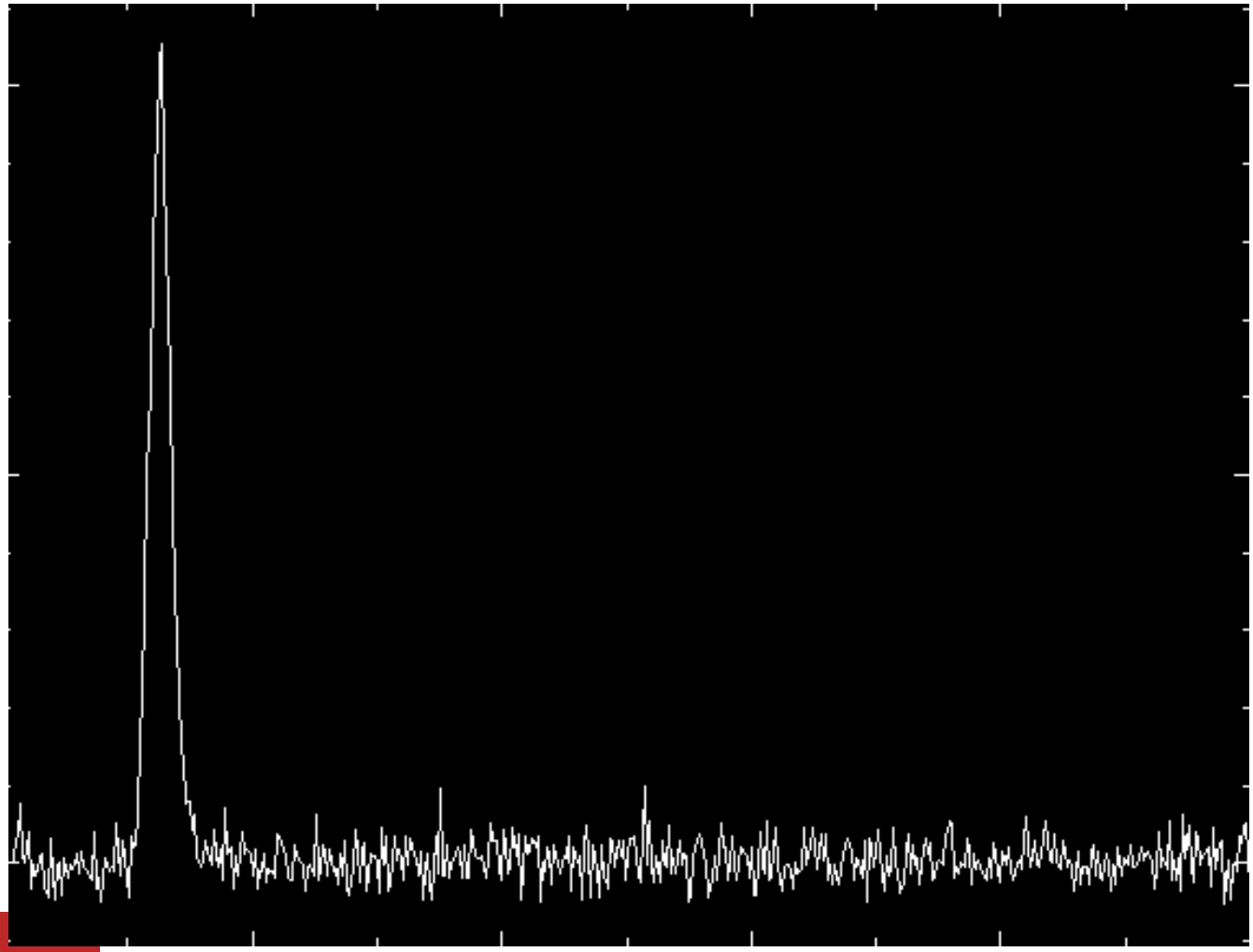

J0835-4510 2009-08-14-12:30:15.ar
Freq: 1382.000 MHz BW: -400.000 Length: 1.000 S/N: 1507.005
Vela Pulsar
DM = 68 pc/cc
Frequency (MHz)
1200
1300
1400
1500
Index
0
200
400
600
800
1000
0
0.2
0.4
0.6
0.8
1
Pulse Phase

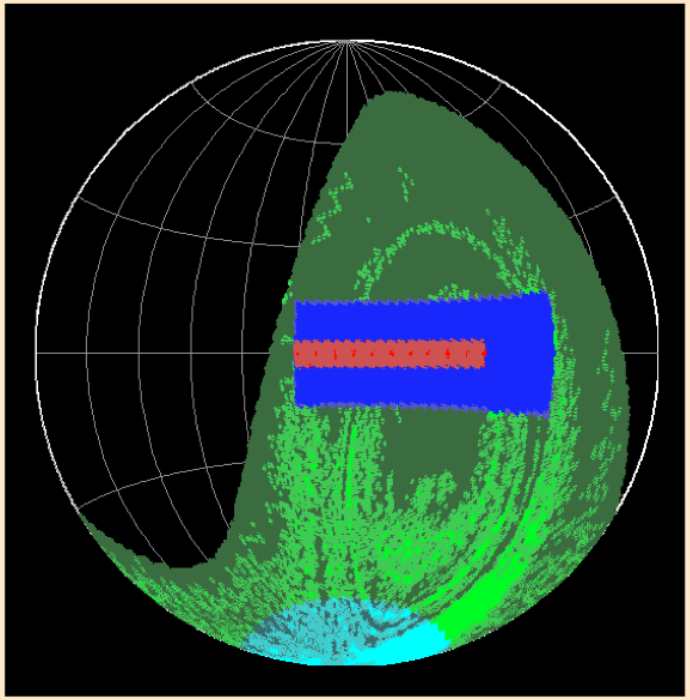

CHEAP Digital Signal Processing
ROACH/iBOB CASPER Tools
Staveley-Smith & Bailes
Danny Price
Andrew Jameson
“HIPSR”

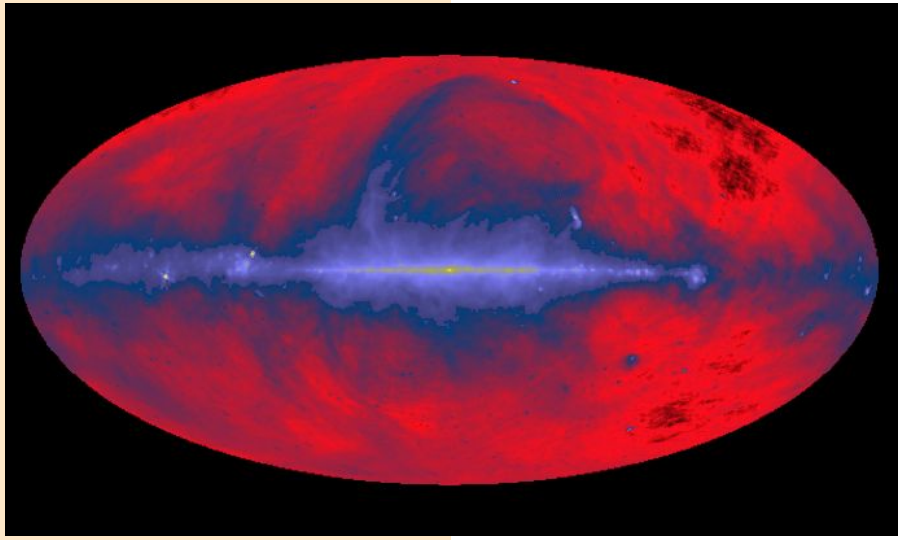

“Diamond Planet” Pulsar
(Bailes et al. 2011)
Prefit Residual (ms)
2
1
0
−1
−2
0
0.5
1
Orbital phase

New Timing Array PSR? (Barr & Coster)



HITRUN Regions





Galactic plane:
70 min/pointing
-80° < gl < 30°
|gb| < 3.5°
1240 pointings
11% observed

Intermediate latitudes:
512 s/pointing
-120° < gl < 30°
|gb| < 15°
6690 pointings
100% observed
99% (56%) processed

All-sky:
256 s/pointing
the remaining southern sky

36450 pointings
18% observed
10% processed

Dan Thornton's burst

- Dan Thornton (U Manchester Ph D student)
- Processing HITRUN Hilat survey for thesis
- Processed ~4,000 Square Degrees (old offline pipeline)
- Single pulse survey
- New exciting single pulse

  detected!

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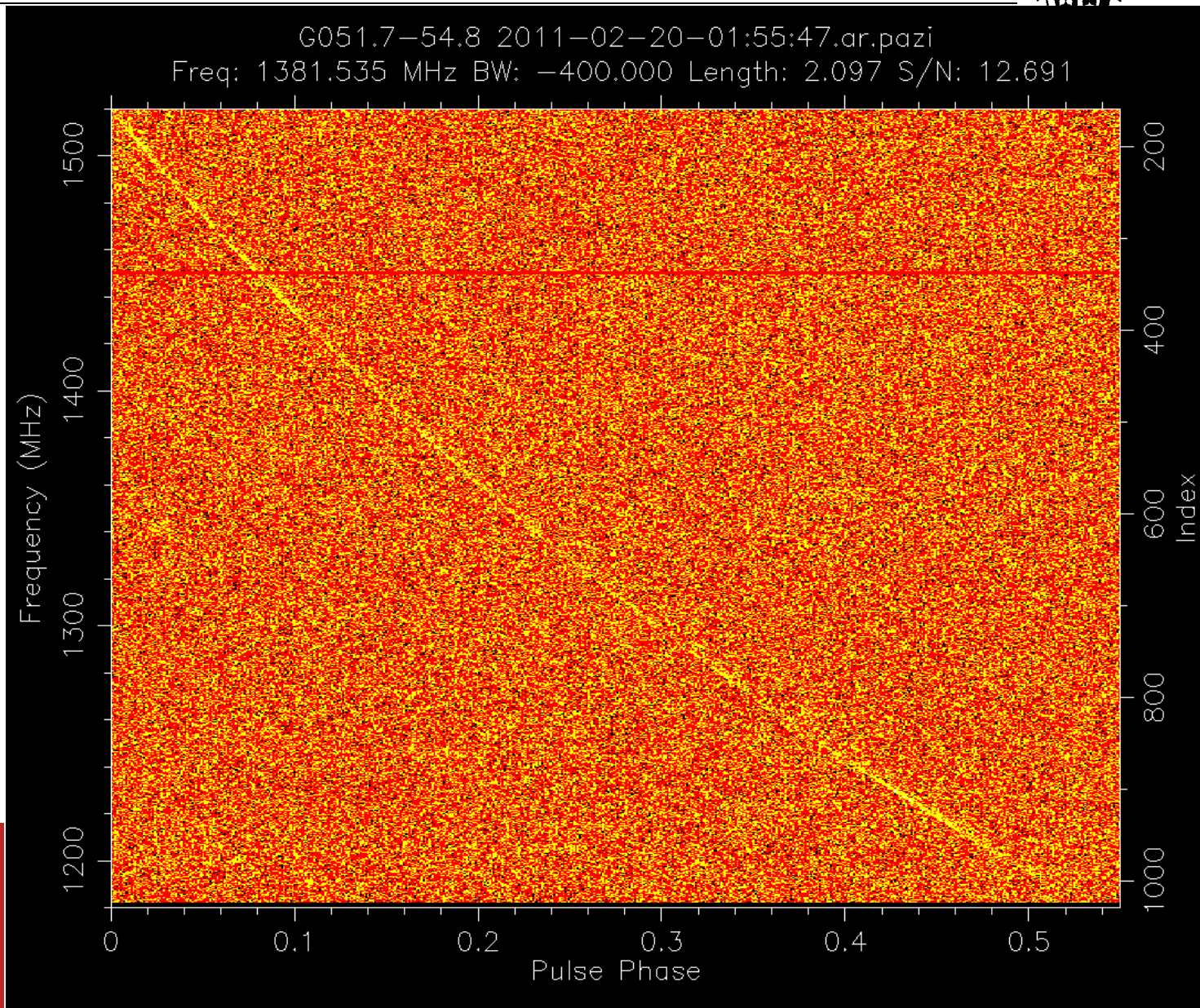
DM >> Lorimer Burst ! Well off galactic plane.

One beam
Only.
Instrumentation
better
Allows detailed
studies

DM~944.38pc/cc!



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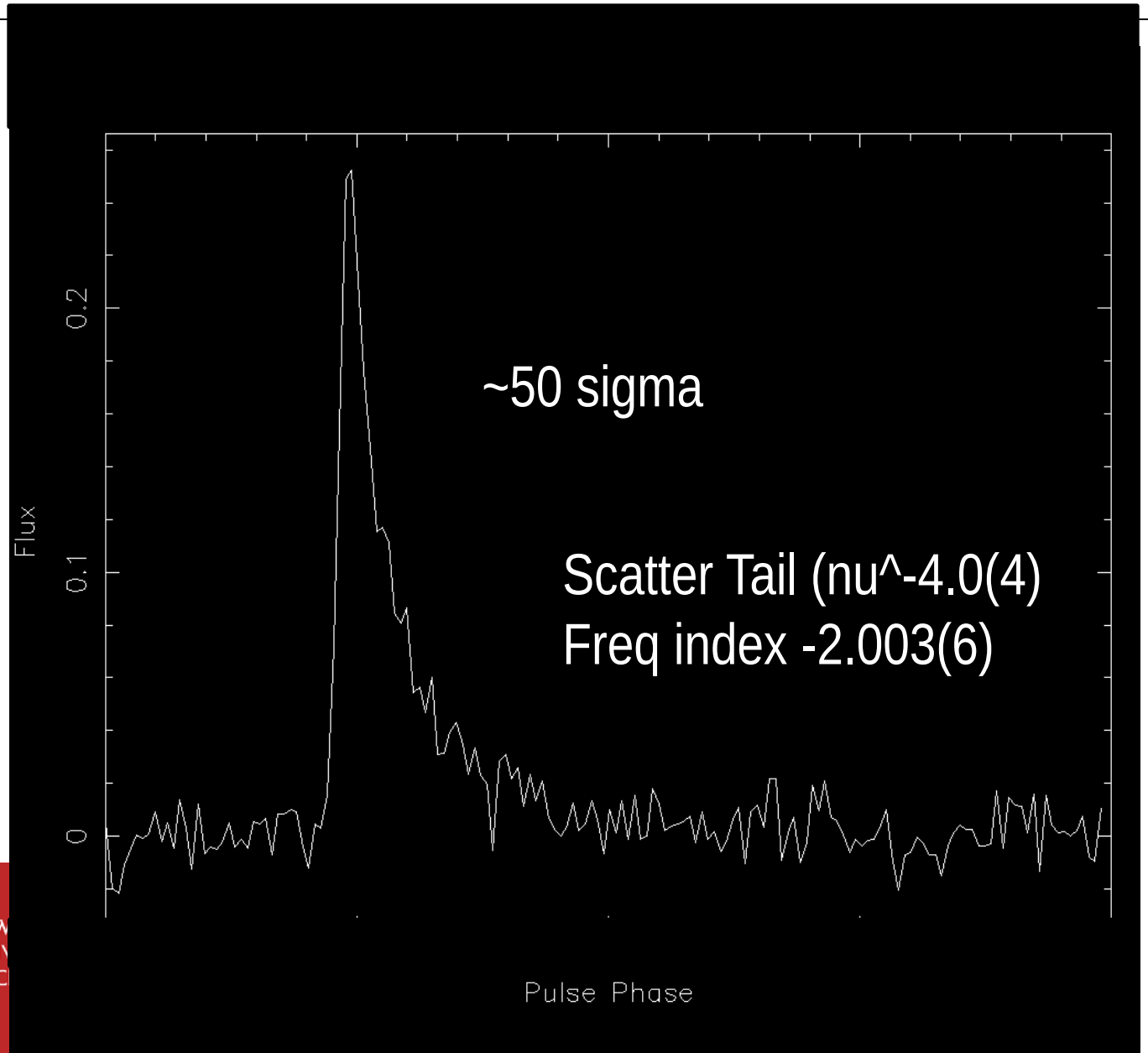
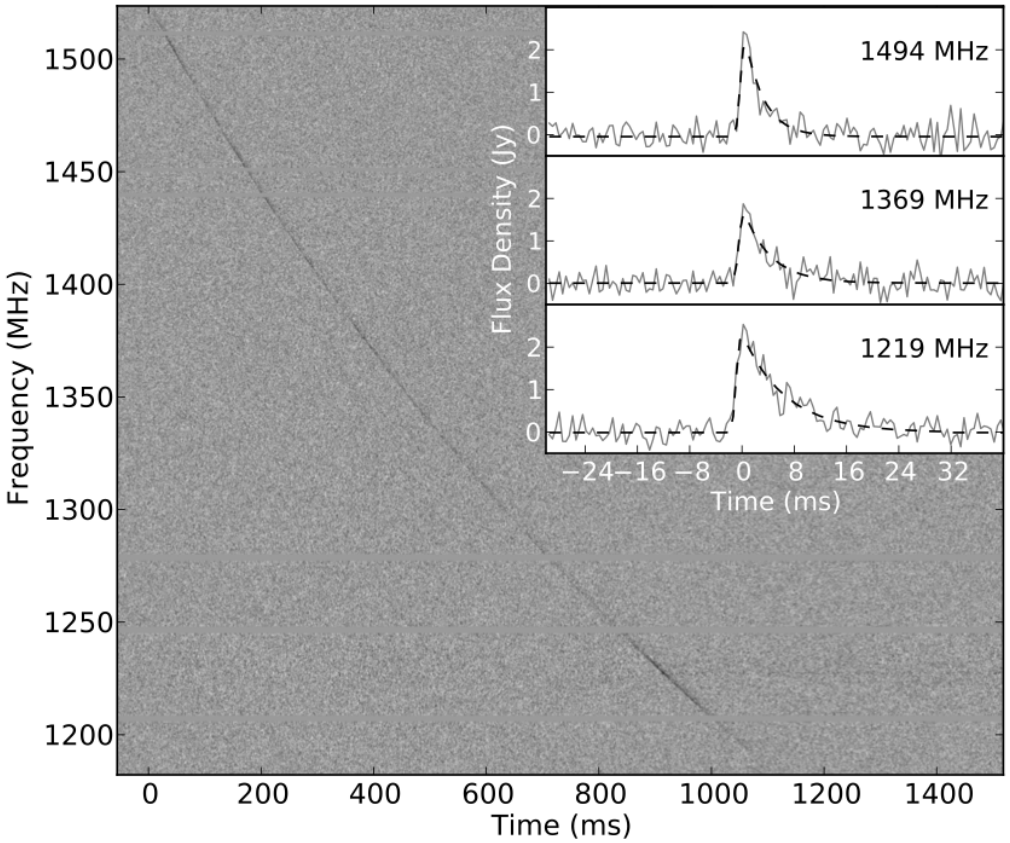
Burst Profile



FRB 110220 – the brightest

- DM = 944 cm^{-3} pc; W = 5.6 ms
- Evidence of scatter broadening



- Bright enough to fit the pulse shape as a fn. of frequency to find dispersion & scattering indices

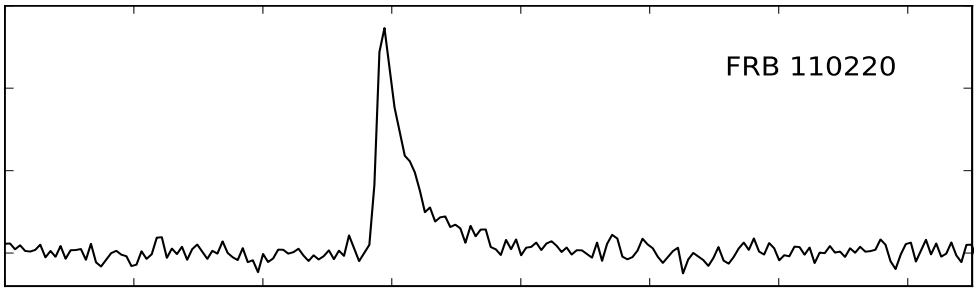
$$\delta t \propto \nu^{-2.003 \pm 0.006}$$

$$W \propto \nu^{-4 \pm 0.4}$$

Intrinsic width unresolved!

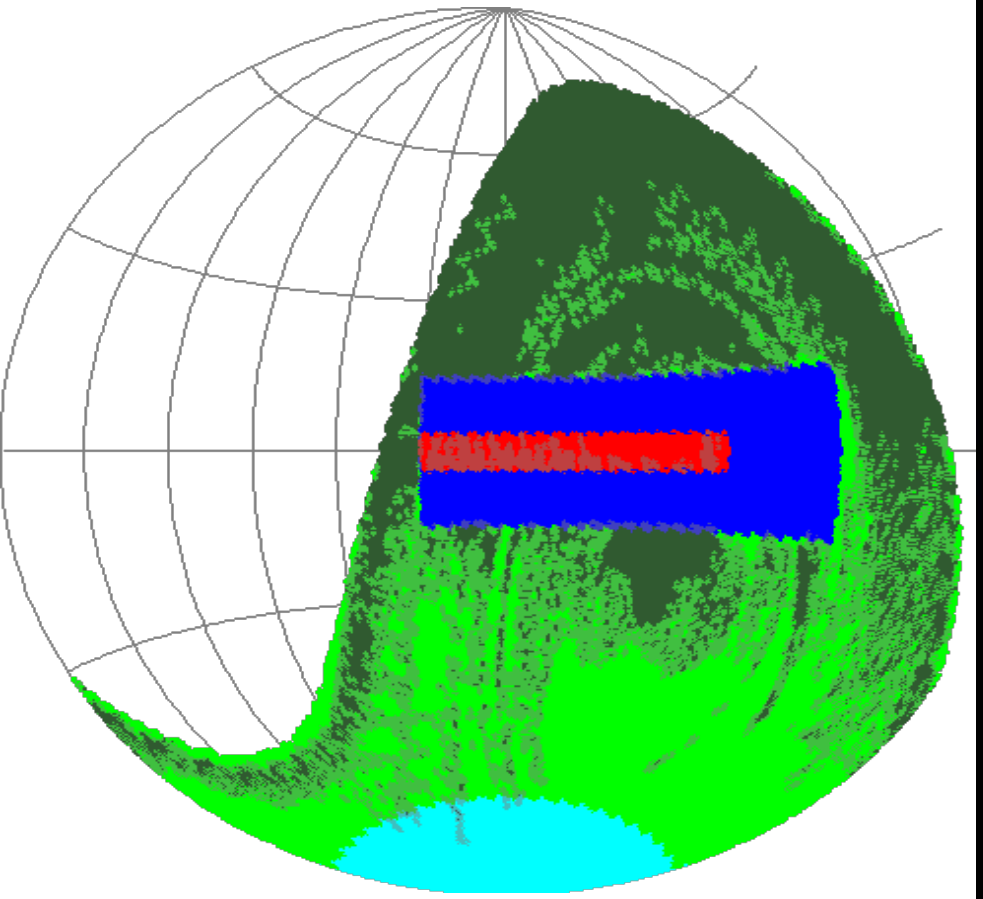
More bursts

- DMs
  - 995 pc/cc
  - 723 pc/cc
  - 1103 pc/cc
  - 553 pc/cc
- + lots more!

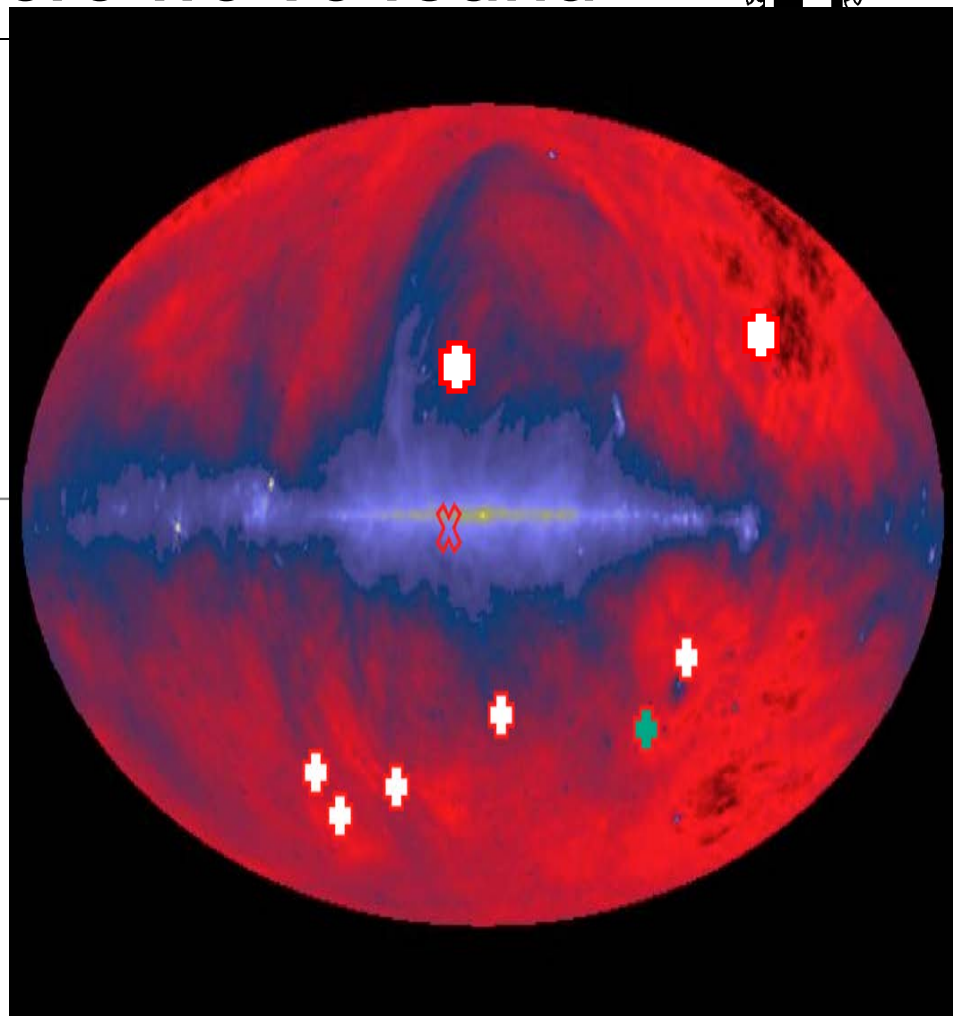


Name	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam Right Ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam Declination (J2000)	–12° 24’	–44° 44’	–02° 52’	–18° 25’
Galactic Latitude, *b* (°)	–54.7	–41.7	–59.0	–66.2
Galactic Longitude, *l* (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy 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

Where we've looked, where we've found



(bit out of date)



If RFI, should see just as many on the plane?

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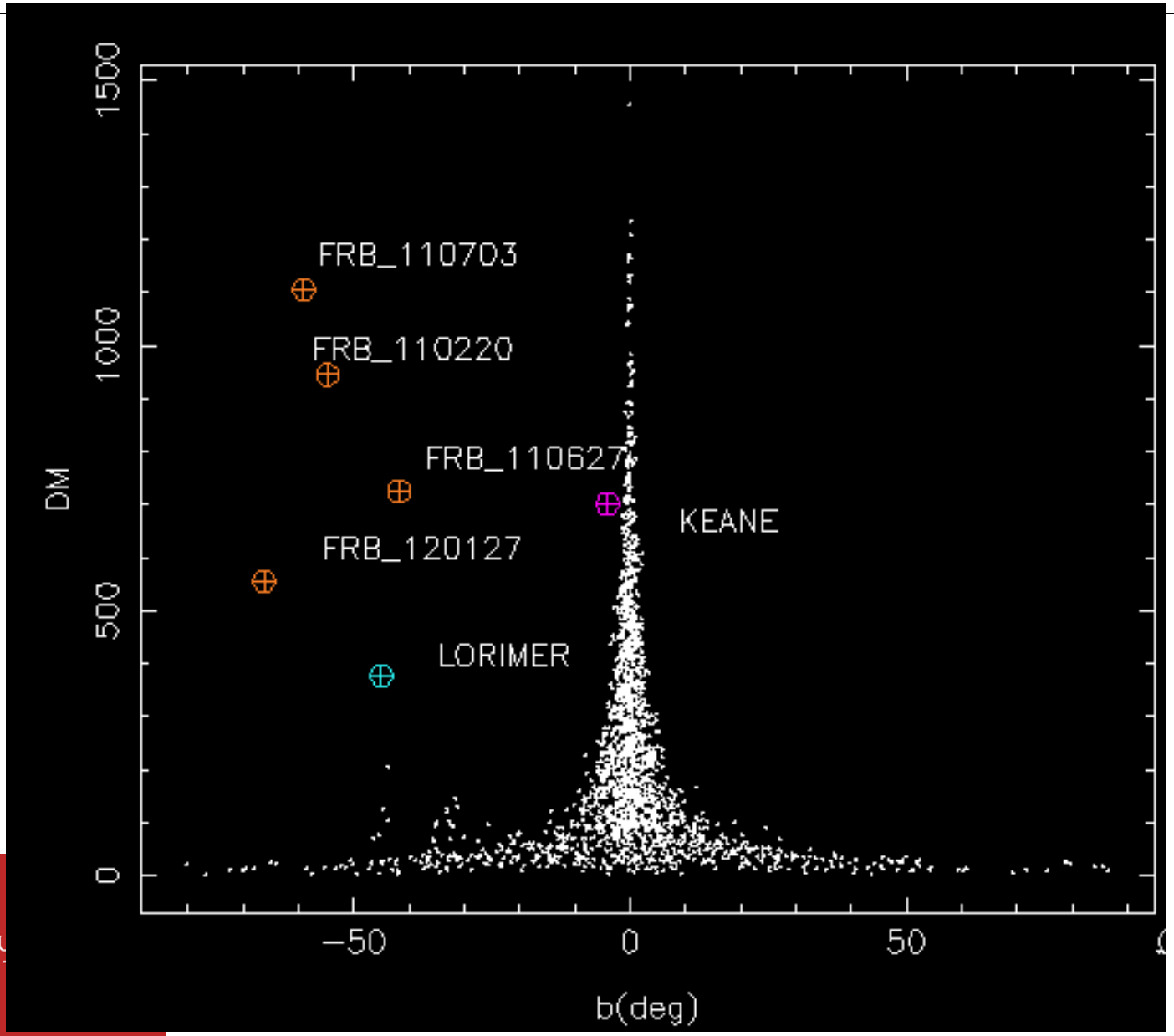
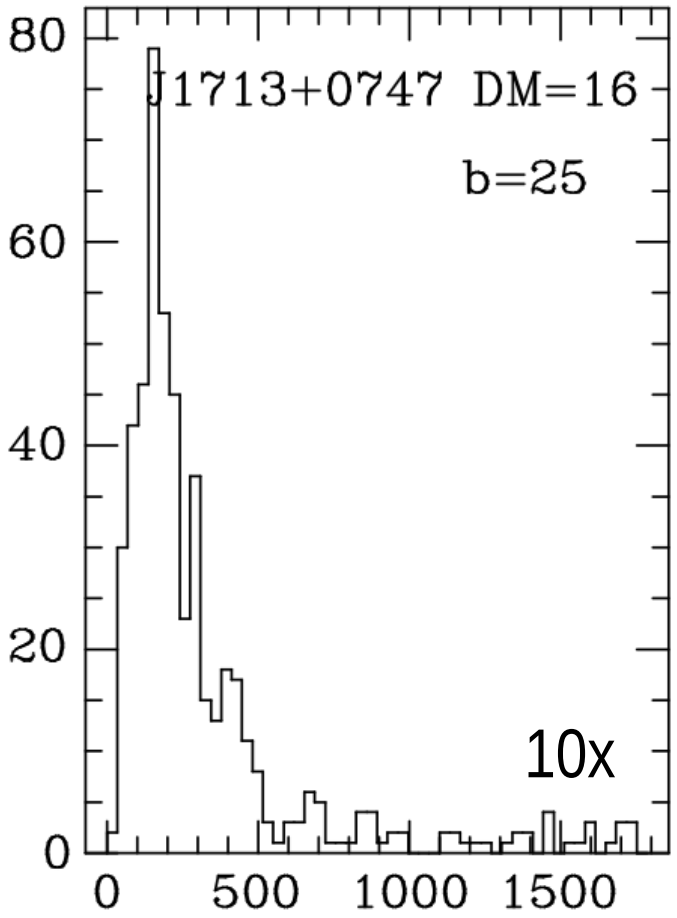
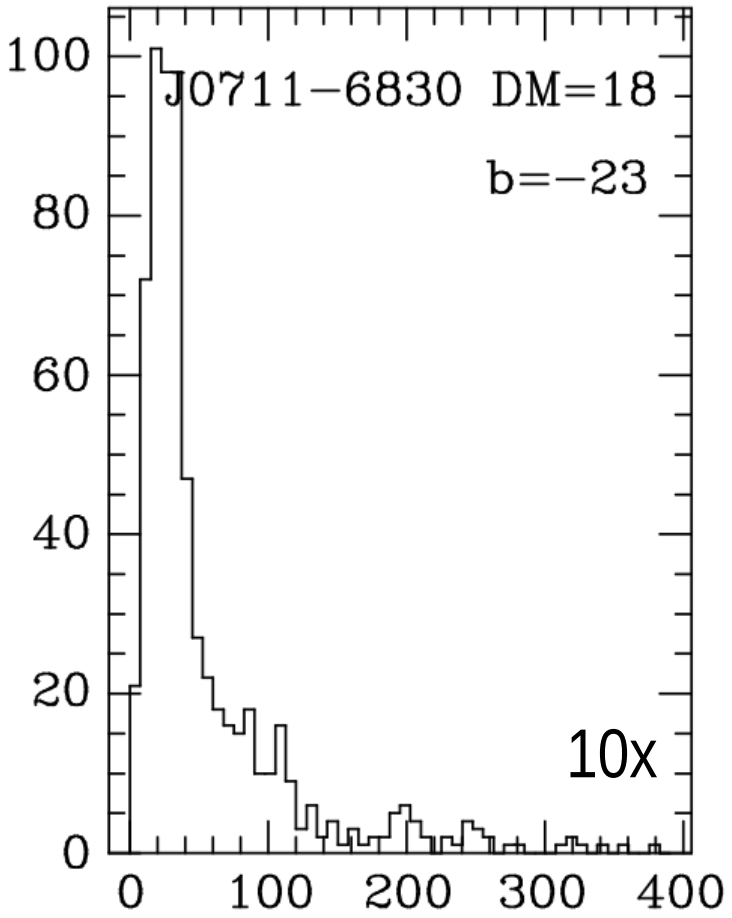
DM and where?


FRB_110703
FRB_110220
FRB_110627
KEANE
FRB_120127
LORIMER
DM
0
500
1000
1500
−50
0
50
b(deg)

Pulsar Fluxes are not constant. Neither are FRBs?





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HITRUN Lorimer Burst Rates

- Implied rates: many thousand/day/sky
  - Too high for ns+ns (SNe?)
- Ours have Z ~0.5-1
- Free electron count of the Universe?
- DM delay to MWA is tens of seconds!
  - Catch one at another telescope?

What is the source of FRBs?

$$R_{\rm FRB} \sim 10^{-3}\ {\rm gal}^{-1}{\rm yr}^{-1}$$

- No known X- or gamma-ray or optical transient that can be associated
  - Previously been tentative radio burst associations to GRBs*

$$R_{\rm GRB} \sim 10^{-6}\ {\rm gal}^{-1}{\rm yr}^{-1}$$

  - Beaming may mean true R_{GRB} is higher by 10^2…**
- Rate is about consistent with core collapse SN rate[§], although no known mechanism for ms radio emission
- Rates probably rule out NS-NS merger[#] events and luminosity black hole evaporations[+]
- SGR giant flare like? Timescale ok, rates?

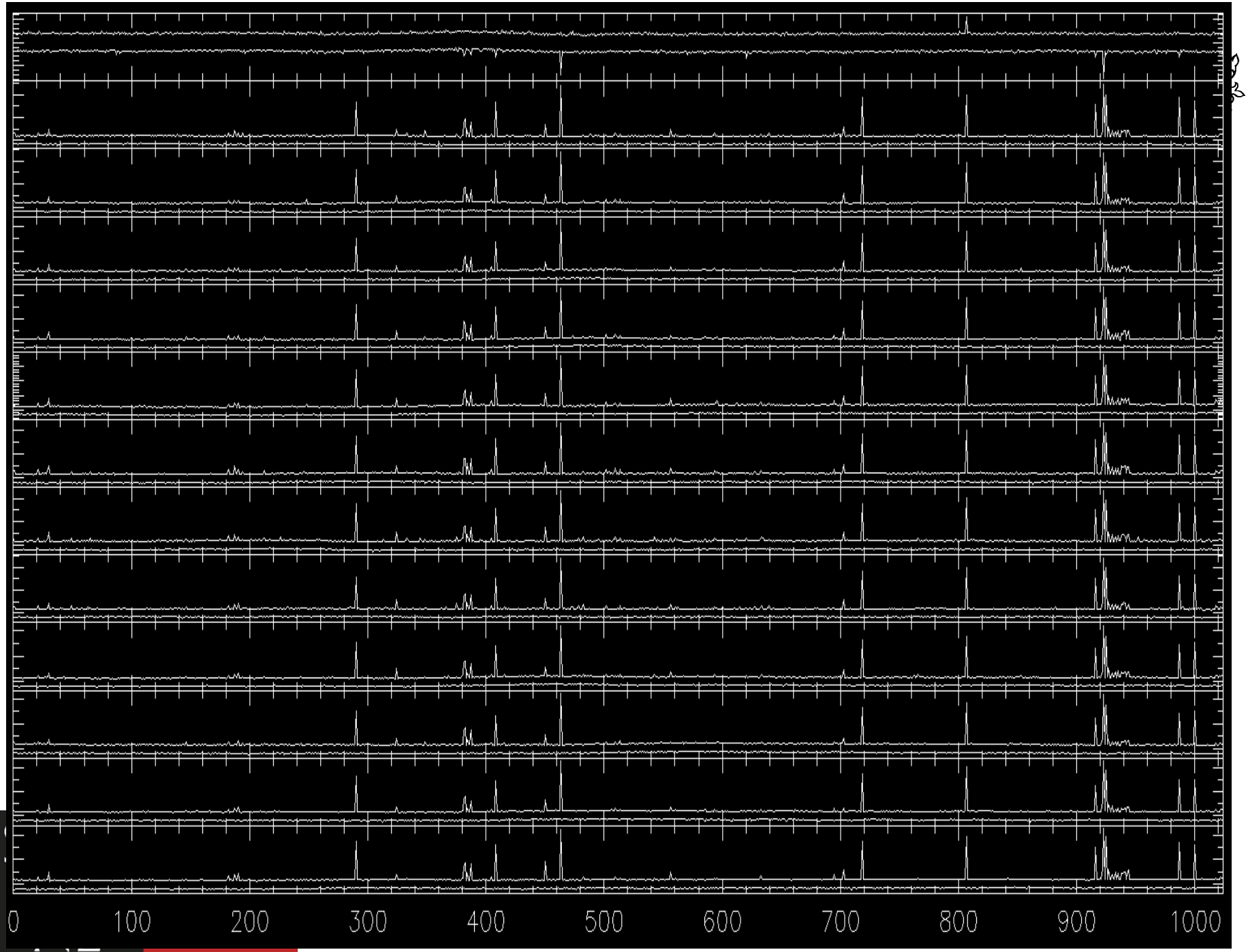
[#]Hansen & Lyutikov (2001); [+]Rees (1977); [§] Diehl, *et al.* (2006); **Frail, *et al.* (2001); *Bannister, *et al.* (2012)

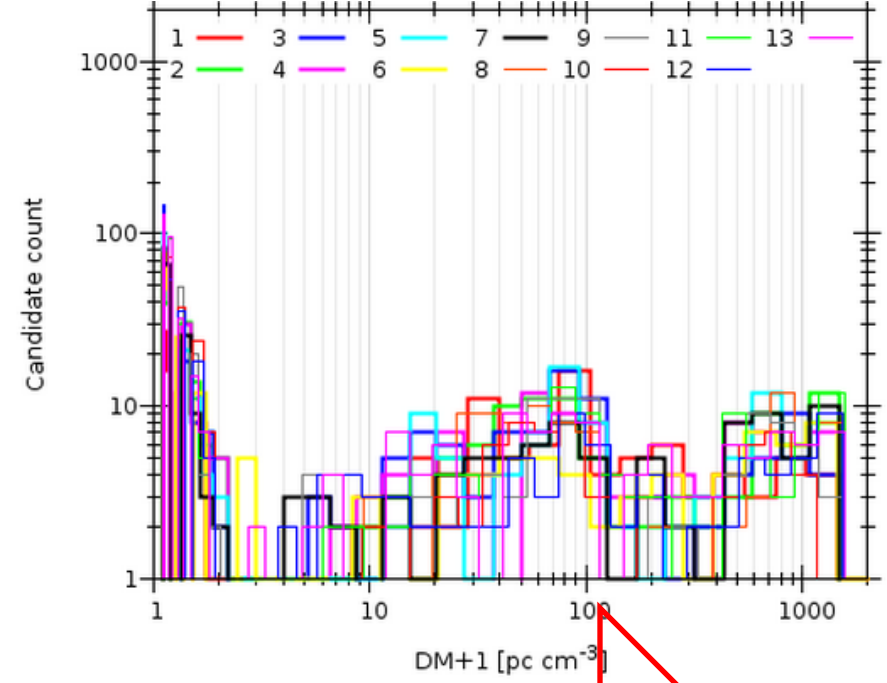
An FRB in our Galaxy?

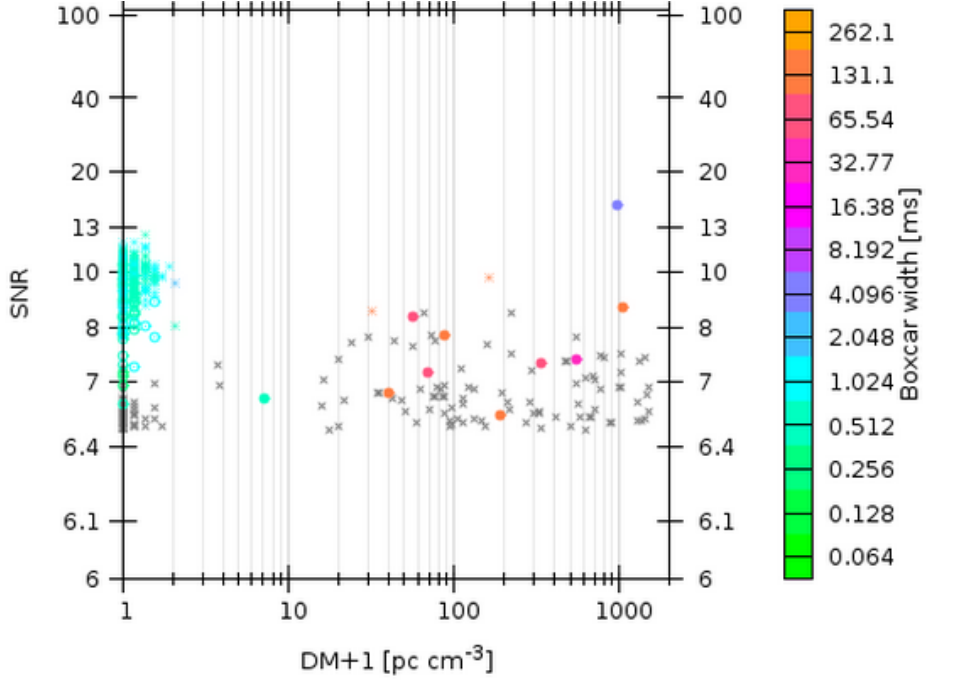
- Thornton has (O) 1 Jy peak
  - 1 Gpc?
- At 10 kpc
  - Flux is 1 Jy * $(1e9/1e4)^2 = 10^{10}$ Jy!
- “Christmas” event
  - 300,000 Lo in 1 ms.
- Parkes observing at the time!
  - Nothing ☹

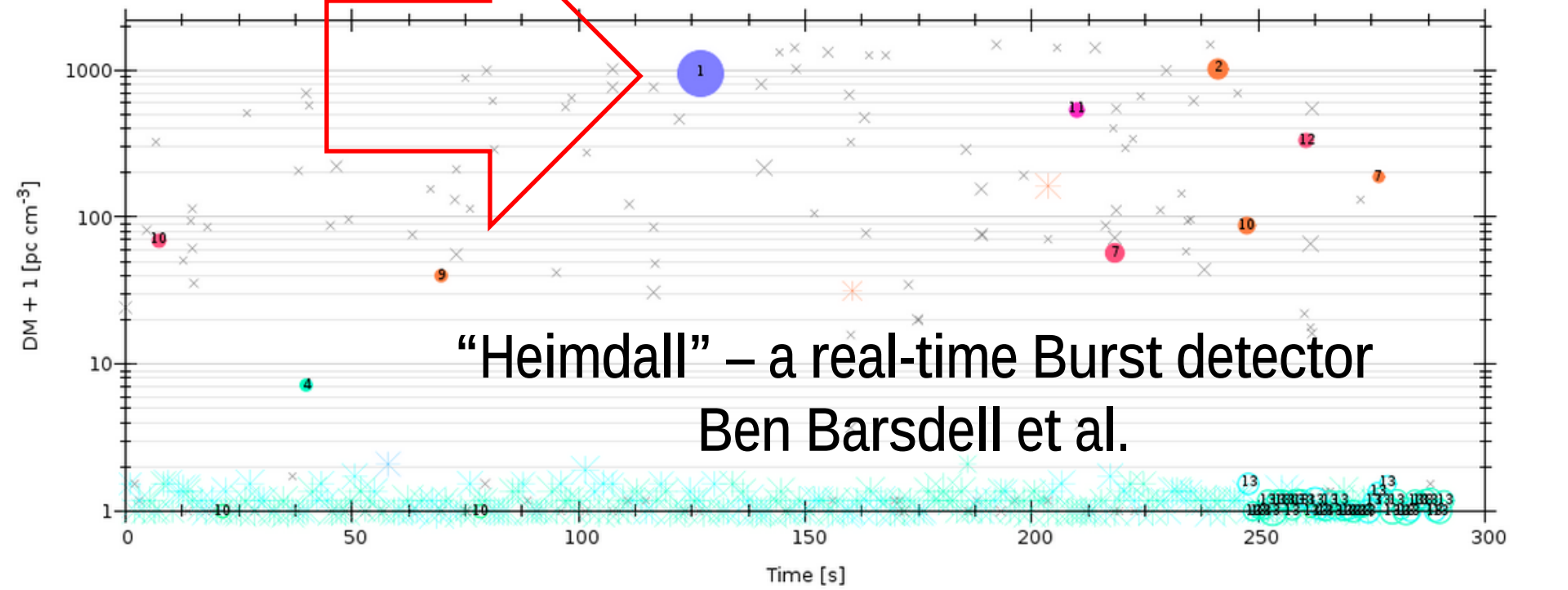
Upgrade #1 real-time detector!

- Uses GPUs to dedisperse and search in real time.
- Ben Barsdell PhD thesis


0
100
200
300
400
500
600
700
800
900
1000







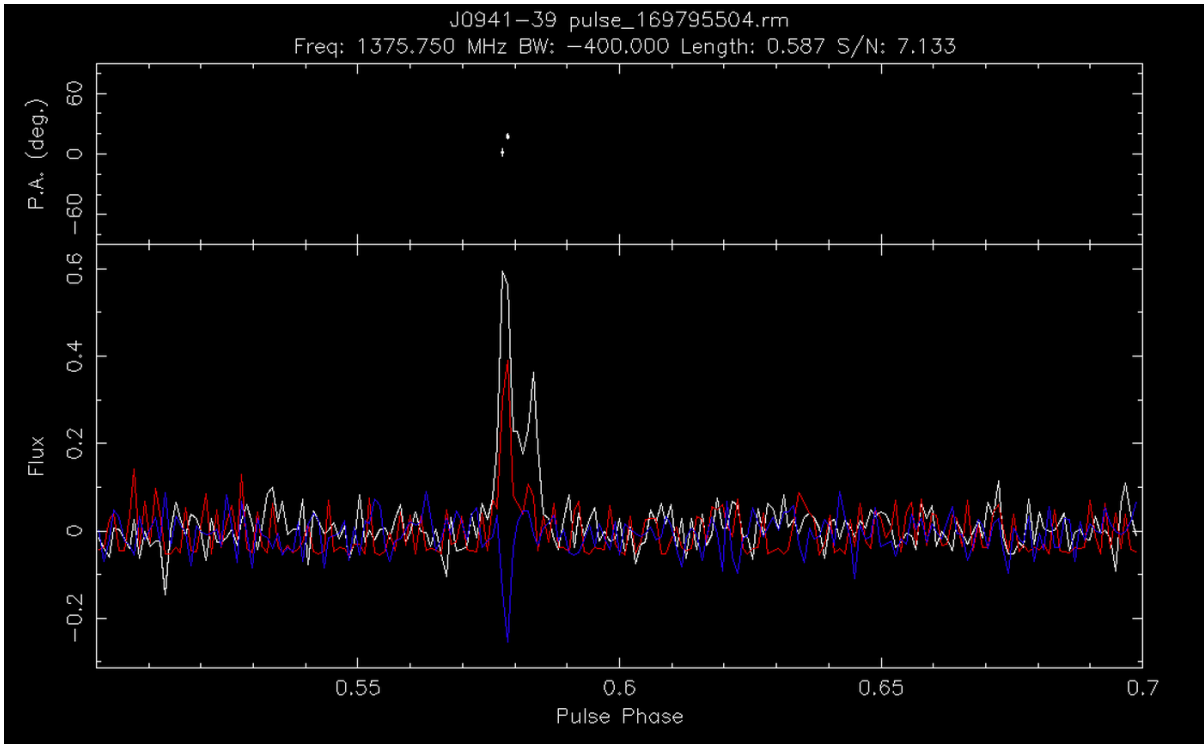
“Heimdall” – a real-time Burst detector

Ben Barsdell et al.

Upgrade #2 – Polarimetry!

ANU collaboration (Briggs & Caleb)

- RM/DM = B|| of the Universe?
  - Missing matter candidate
- Reprogram ROACH + real-time detector + 4xStokes.
- Now just software



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Molonglo Radio Telescope

Anne Green:Telescope Director

Duncan Campbell-Wilson →

Dick Hunstead (Sydney)

Tim Bateman (CASS)

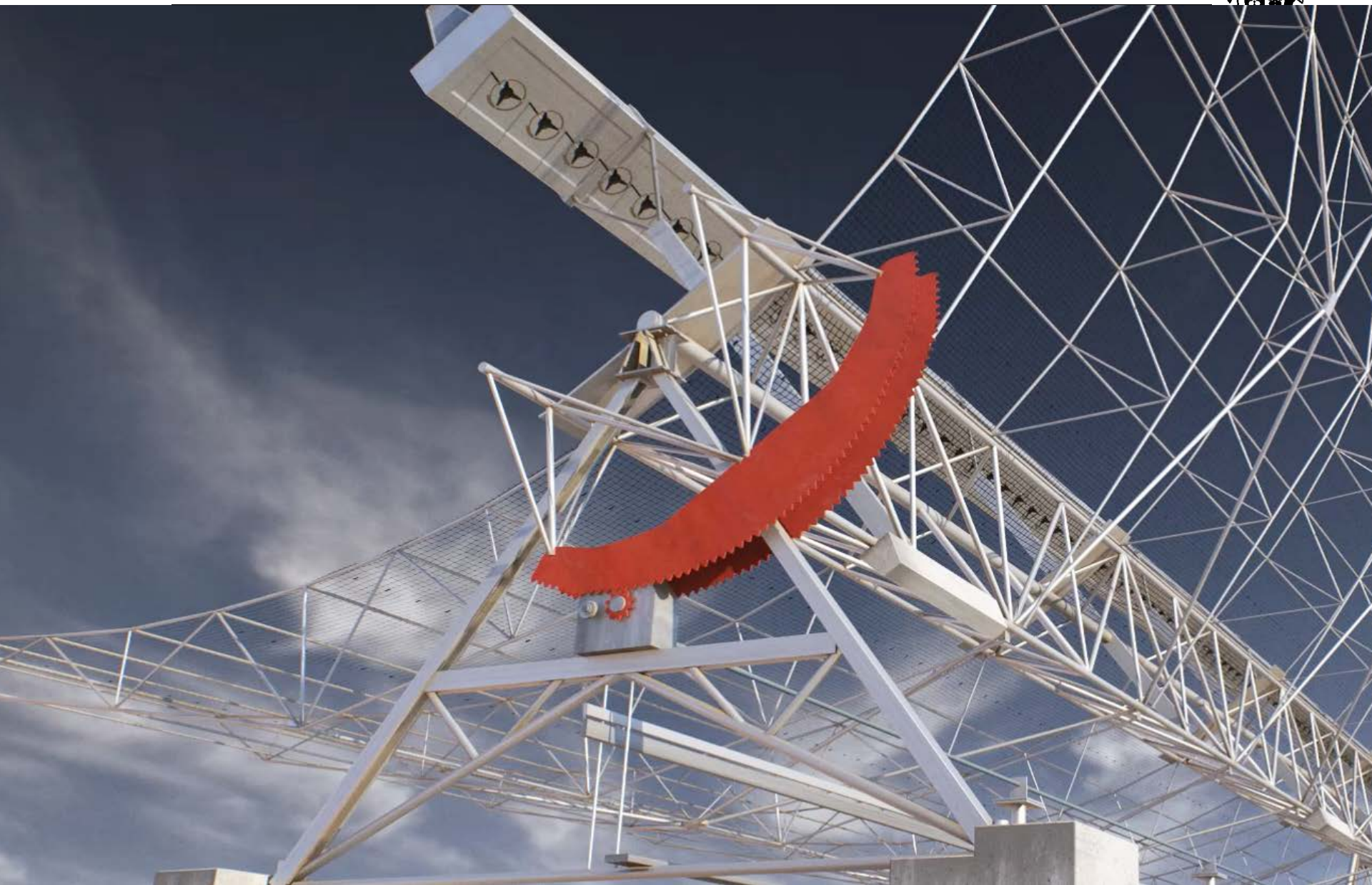
Russ McWhirter (Haystack)

Andrew Jameson (Swinburne)

Matthew Bailes, Ewan Barr, Chris Flynn, Evan Keane, Fabian Jankowski (Swinburne)

Manisha Caleb (ANU), Nie Jun (Urumqi)

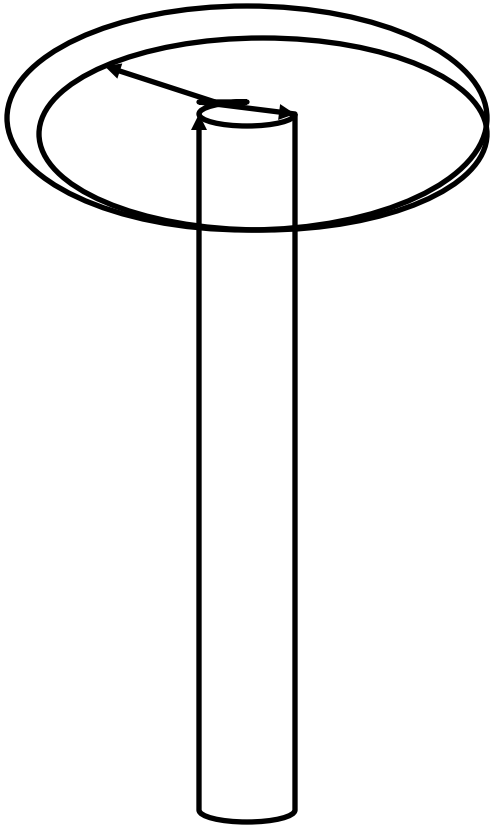
Molonglo



Background

- MOST is the largest radio telescope in Australia: 5xPKS, 4xASKAP
- Development work on digital back-end began around 2005: PFB + correlator, 100 MHz BW, 700-1100 MHz
  - Project backend stalled.
- August 2012 Swinburne floated alternative correlator solution: GPU cluster, with fast sampling (10 Gb/s, 10 GbE)

Smallest element:



- RH Circular Polarisation
- 843 MHz
- ~20 cm apart
- 0.2 x 11 metres wide
- ~2.2 m^2 “telescope”
- 7,744 ring antennae
- ~18,000 m^2
- Sensitivity ~ 0.3-0.5 x PKS

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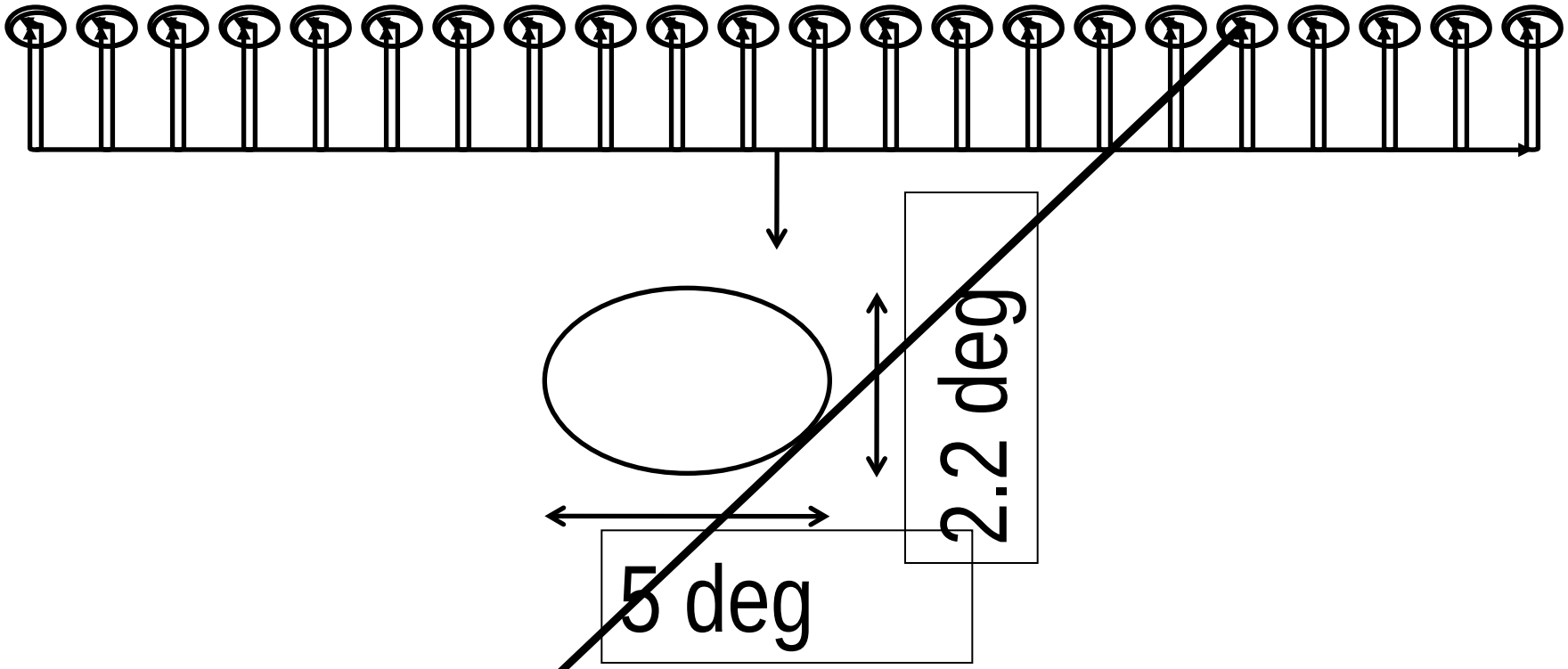
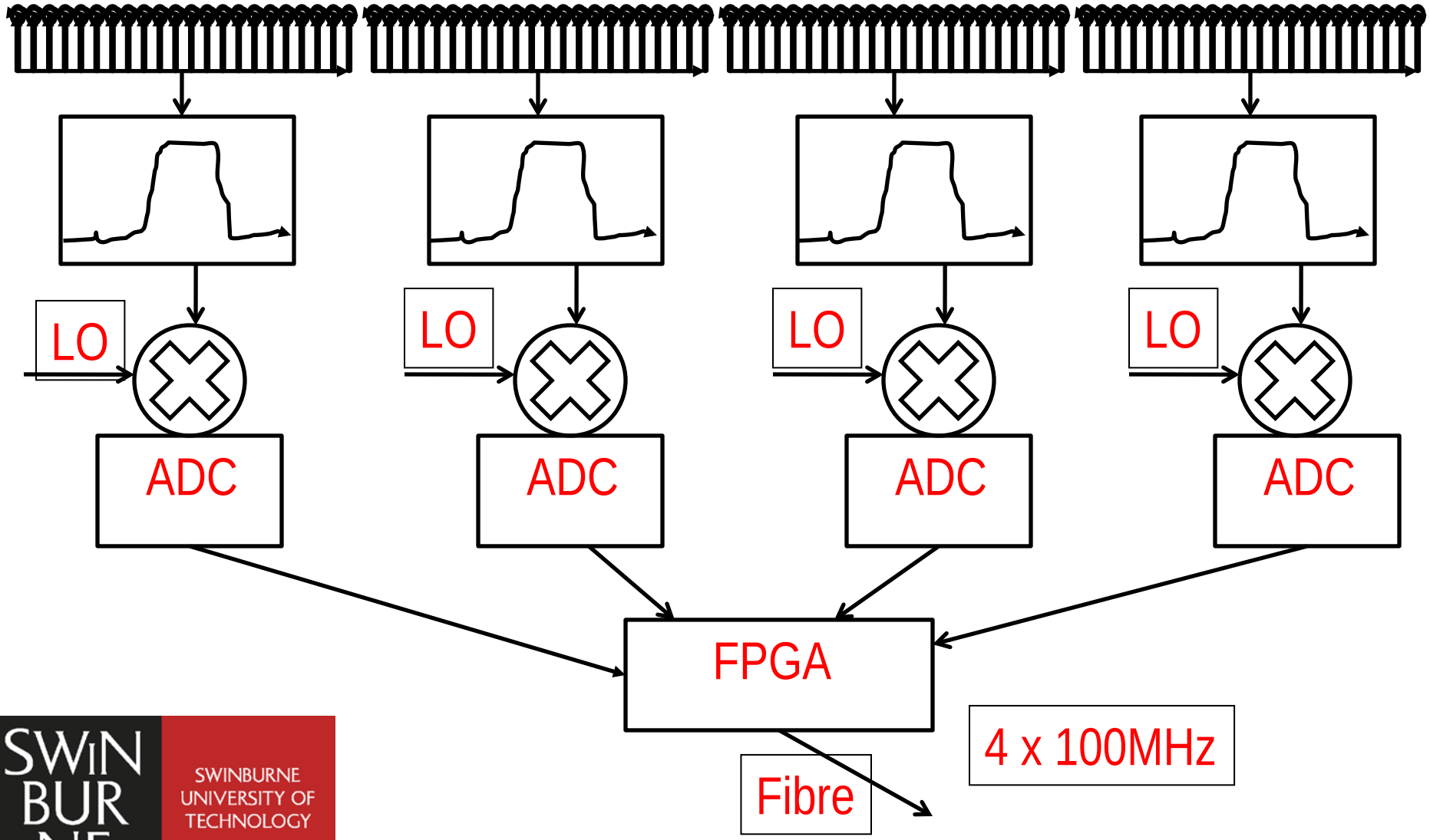
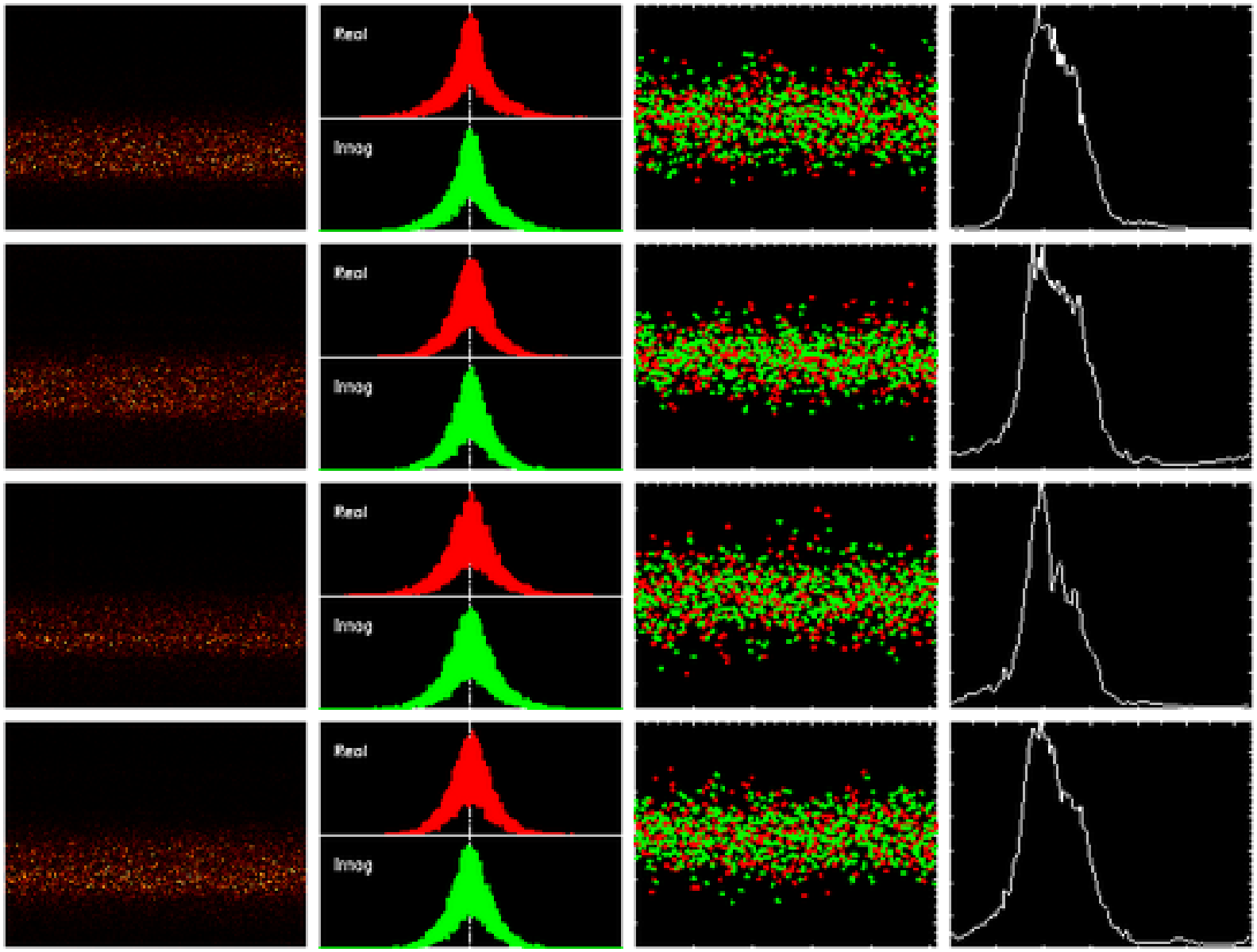
“Add by 22 = Phased array Beam”



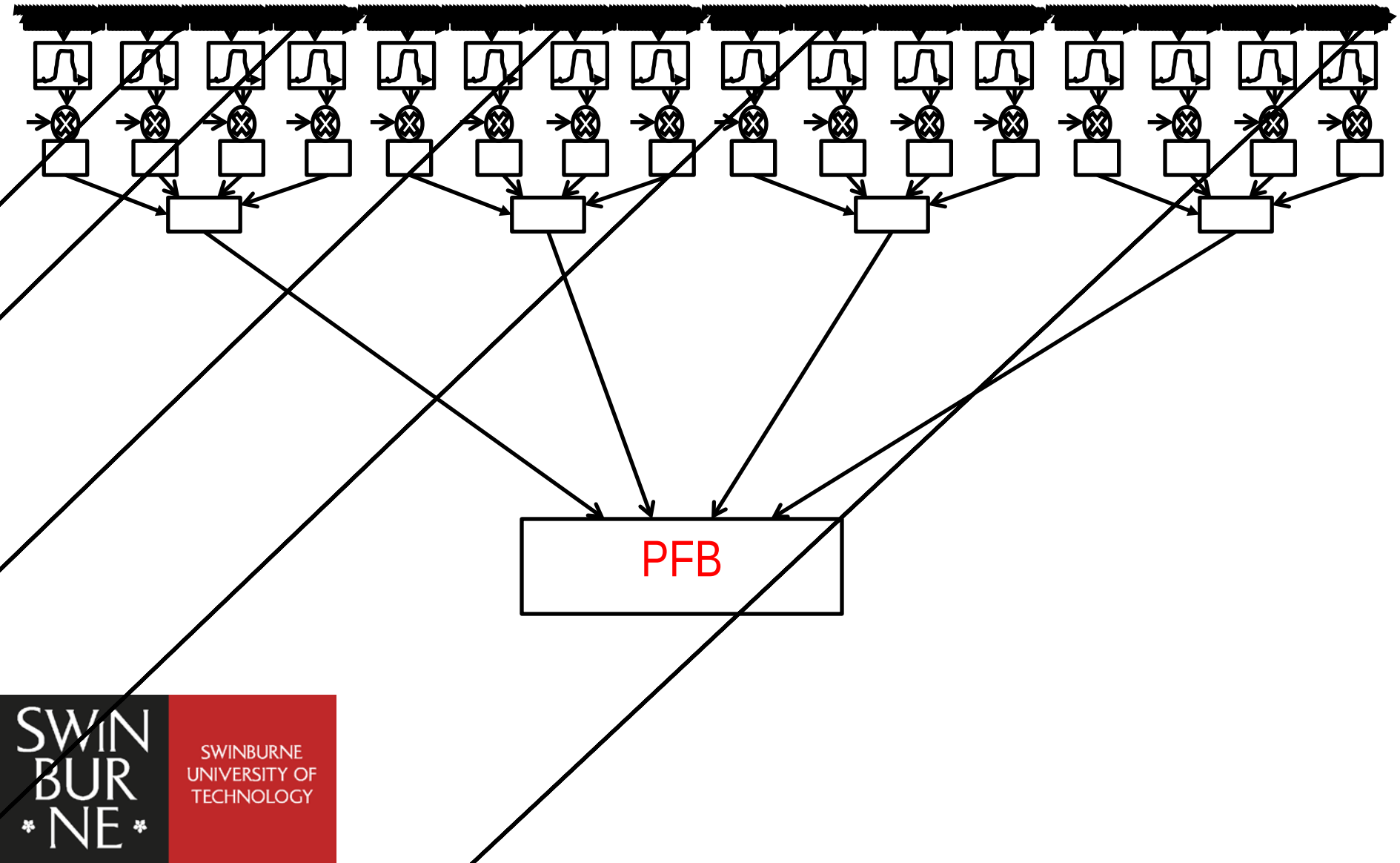
Receivers take 4 “Modules” = 1 “Bay”



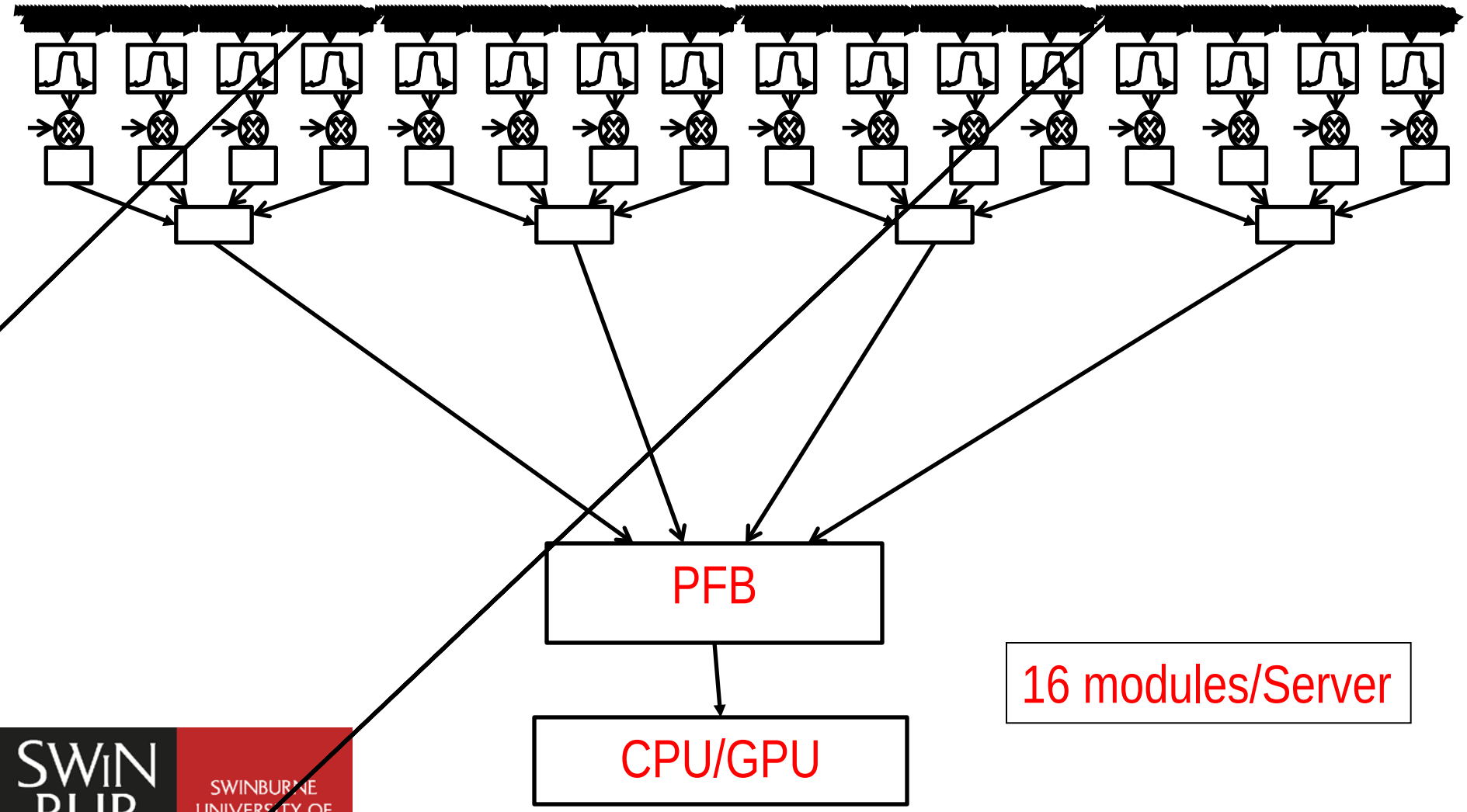
Example of new RX board on sky!



4 x 4 modules = Hex

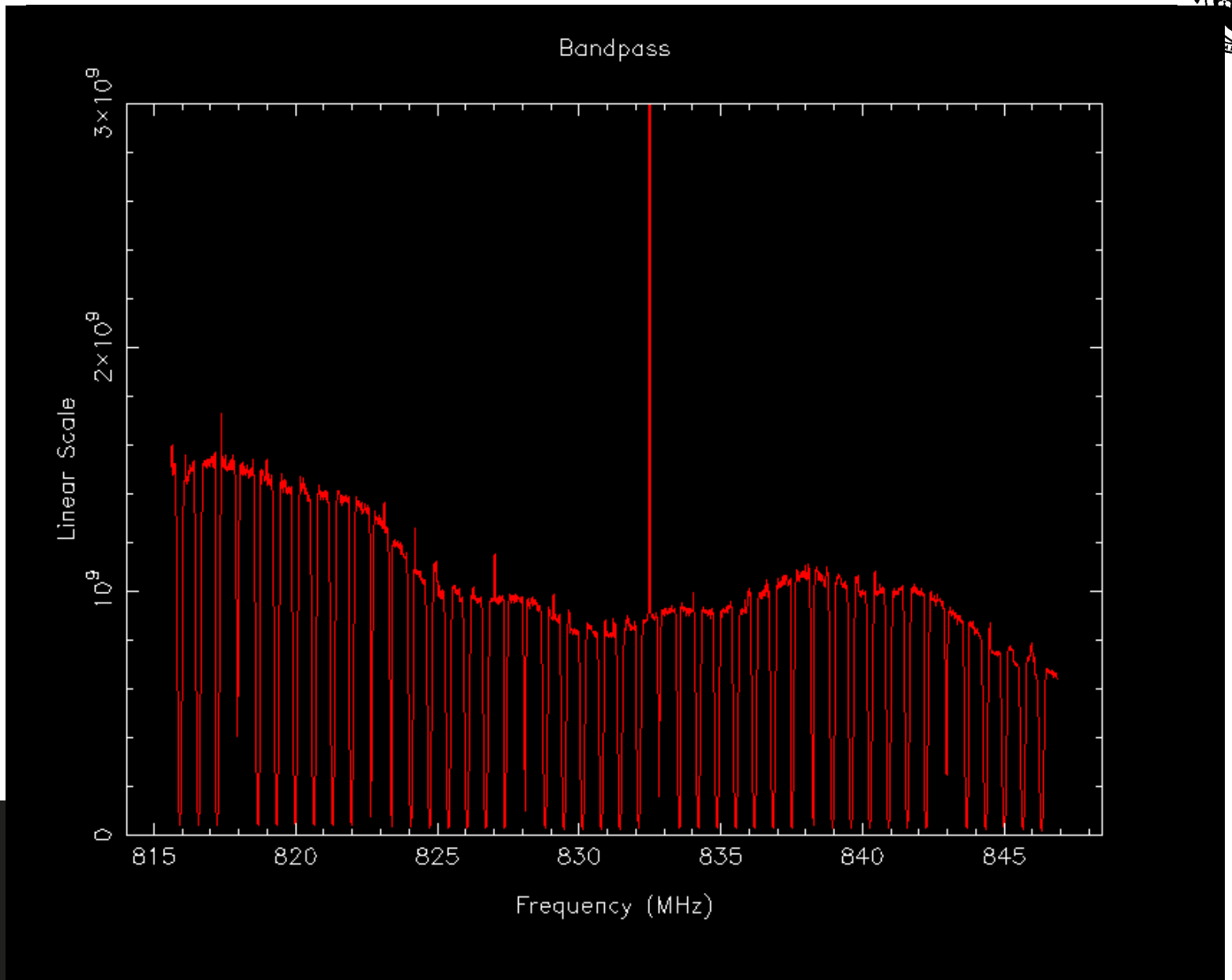


First CPU/GPU Design (use CX4 port)

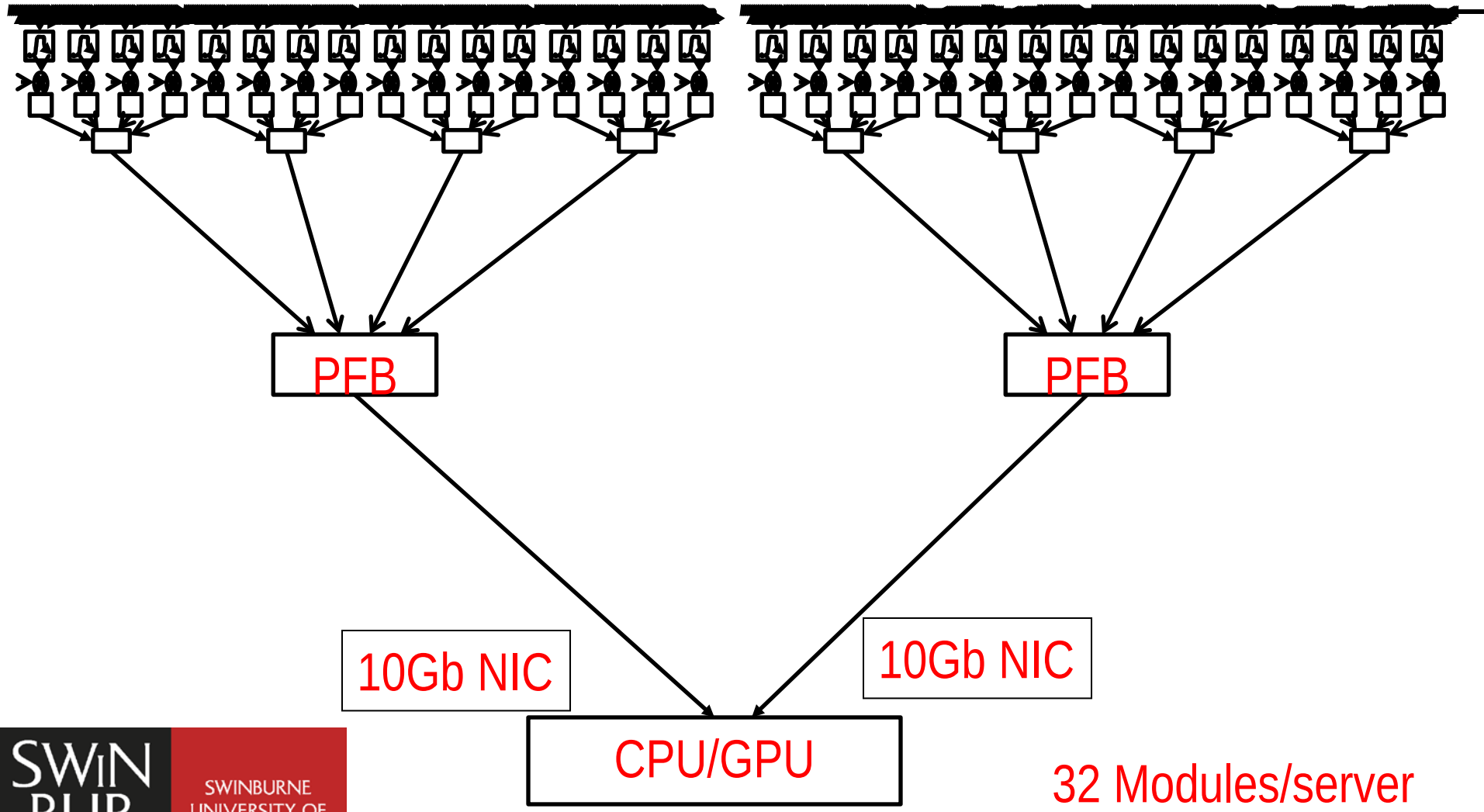


16 modules/Server

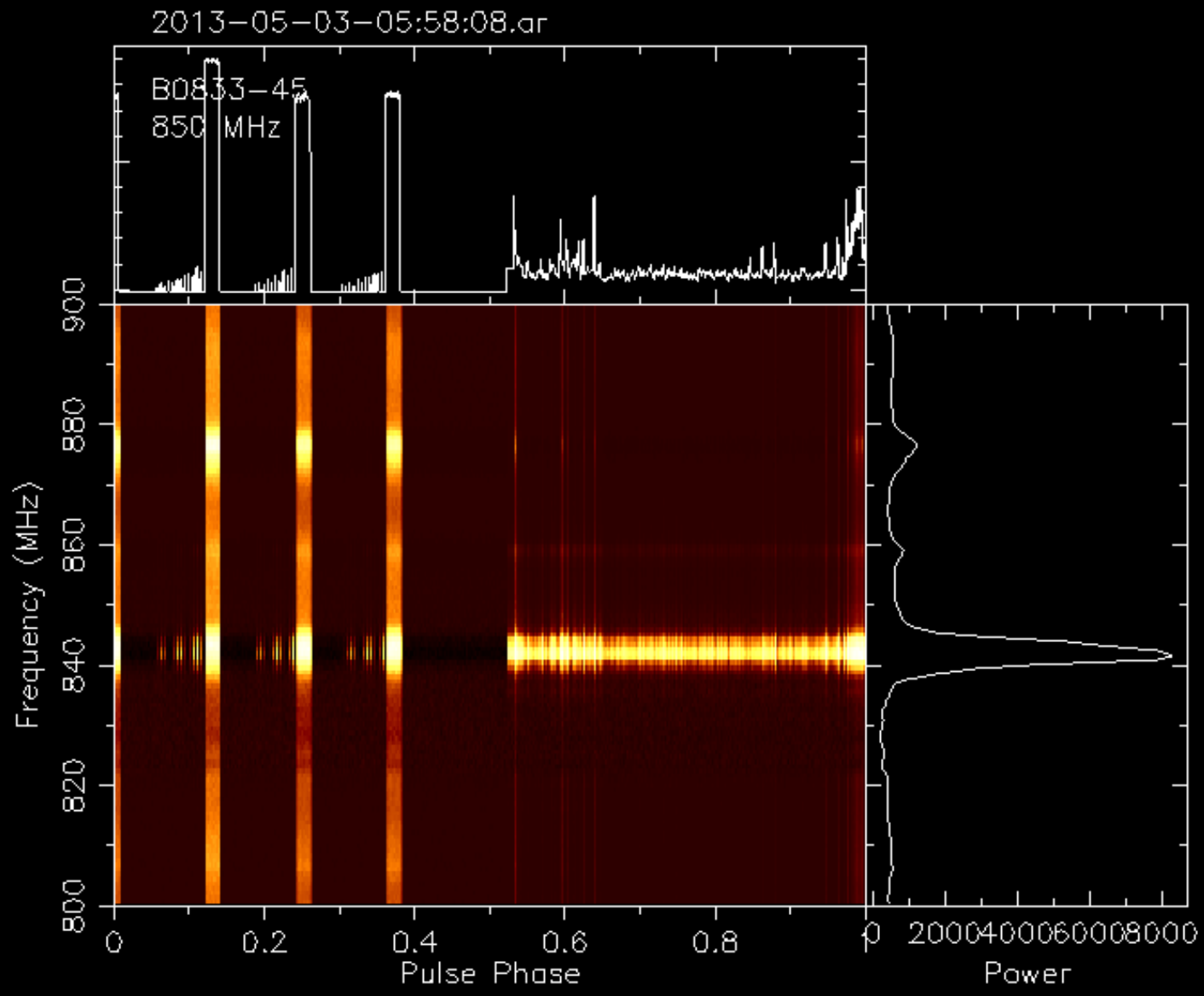
Bandpass


Bandpass
3×10^9
2×10^9
10^9
0
Linear Scale
815
820
825
830
835
840
845
Frequency (MHz)

New CPU/GPU Design (dual 10Gb NIC)



32 Modules/server


2013-05-03-05:58:08.ar
B0833-45
850 MHz
Frequency (MHz)
900
880
860
840
820
800
0
0.2
0.4
0.6
0.8
Pulse Phase
0
2000
4000
6000
8000
Power

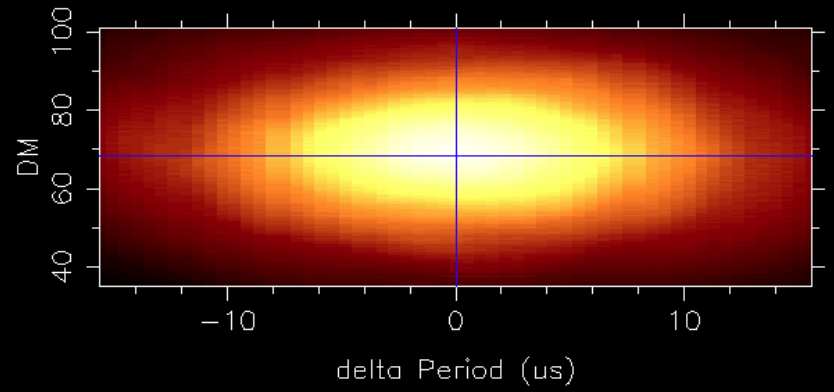
B0833−45: vela_128chan_grand.ar.pazi.pazi

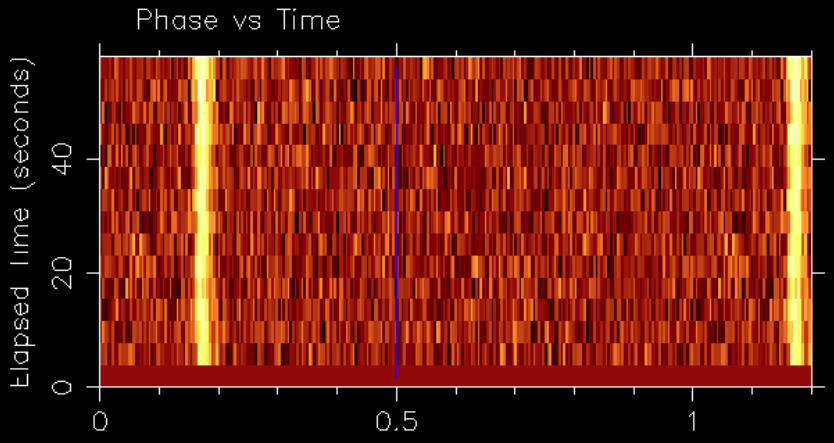
BC P(ms)= 89.388772167 TC P(ms)= 89.383783728 DM= 67.990 RAJ= 00:00:00.00 DecJ= 00:00:00.0

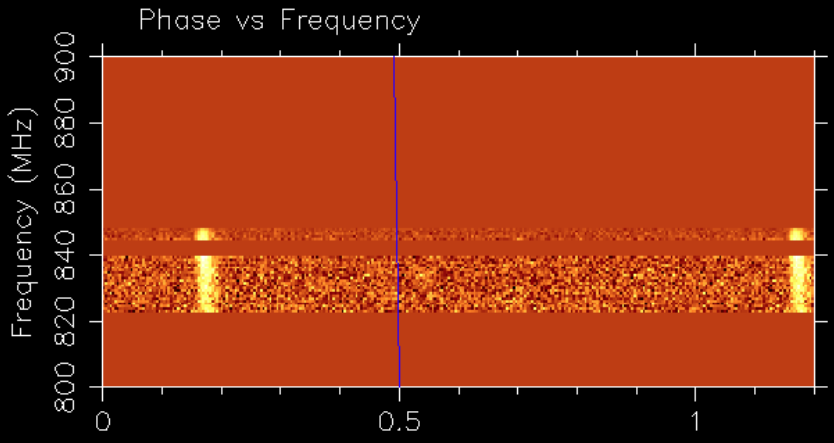
BC MJD = 56408.343160 Centre freq(MHz) = 850.000 Bandwidth(MHz) = 100 l = 96.337 b = −60.189

NBin = 256 NChan = 128 NSub = 15 TBin(ms) = 0.349 TSub(s) = 2.000 TSpan(s) = 57.971

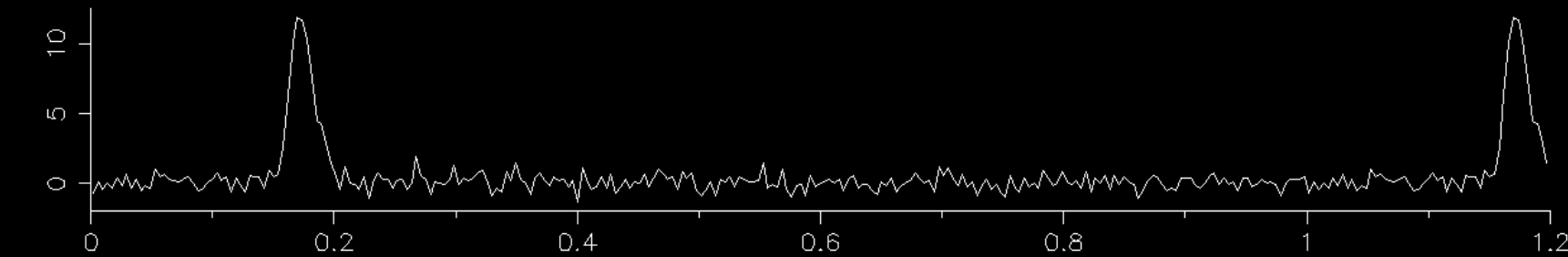
P(us): offset = 0.00000, step = 0.53835, range = 15.60441 DM: offset = 0.000, step = 0.129, range = 33.068



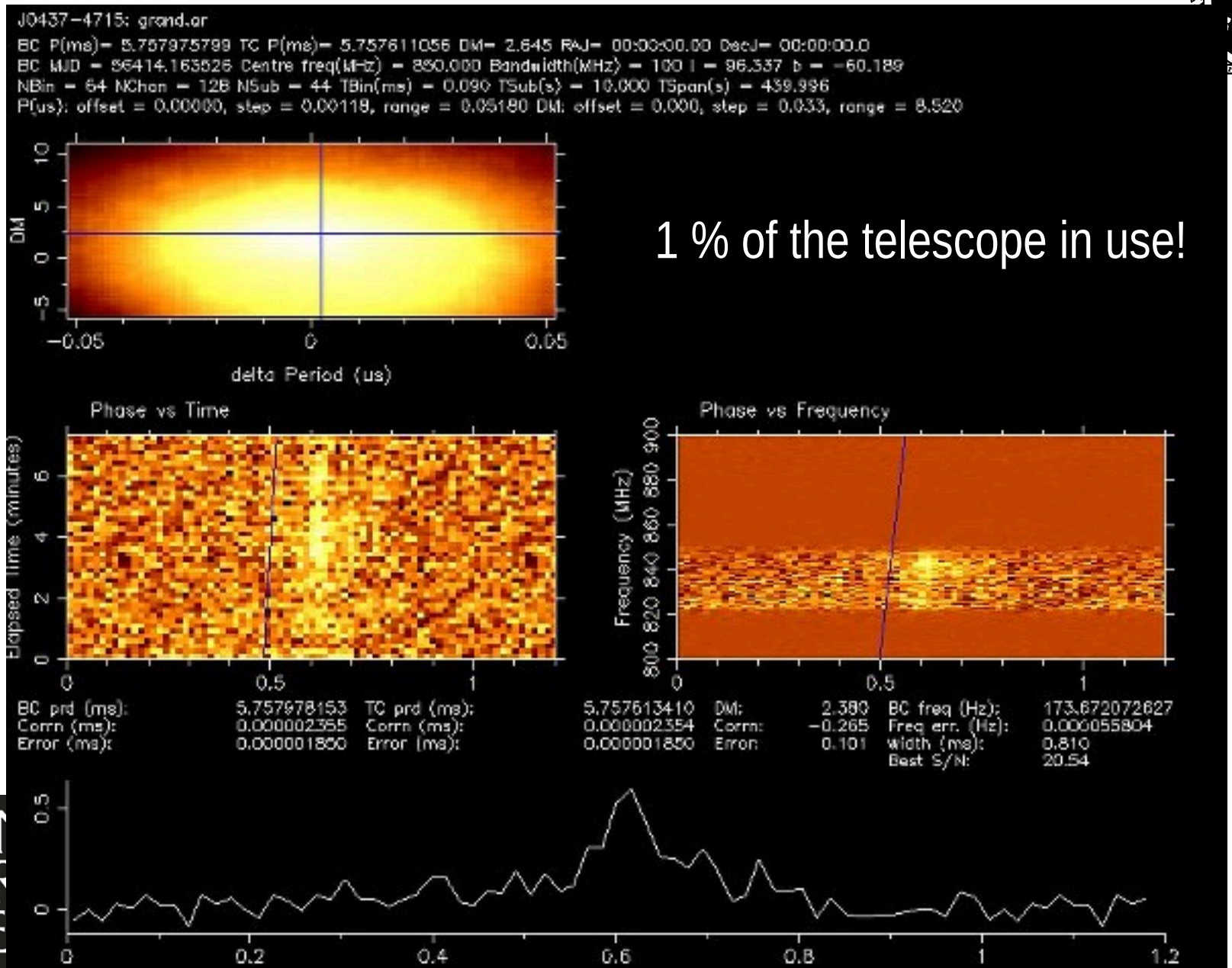




BC prd (ms):	89.388772167	TC prd (ms):	89.383783728	DM:	68.505	BC freq (Hz):	11.187087324
Corrn (ms):	0.000000000	Corrn (ms):	0.000000000	Corrn:	0.515	Freq err. (Hz):	0.000108507
Error (ms):	0.000867009	Error (ms):	0.000867009	Error:	0.391	Width (ms):	2.095
						Best S/N:	48.41

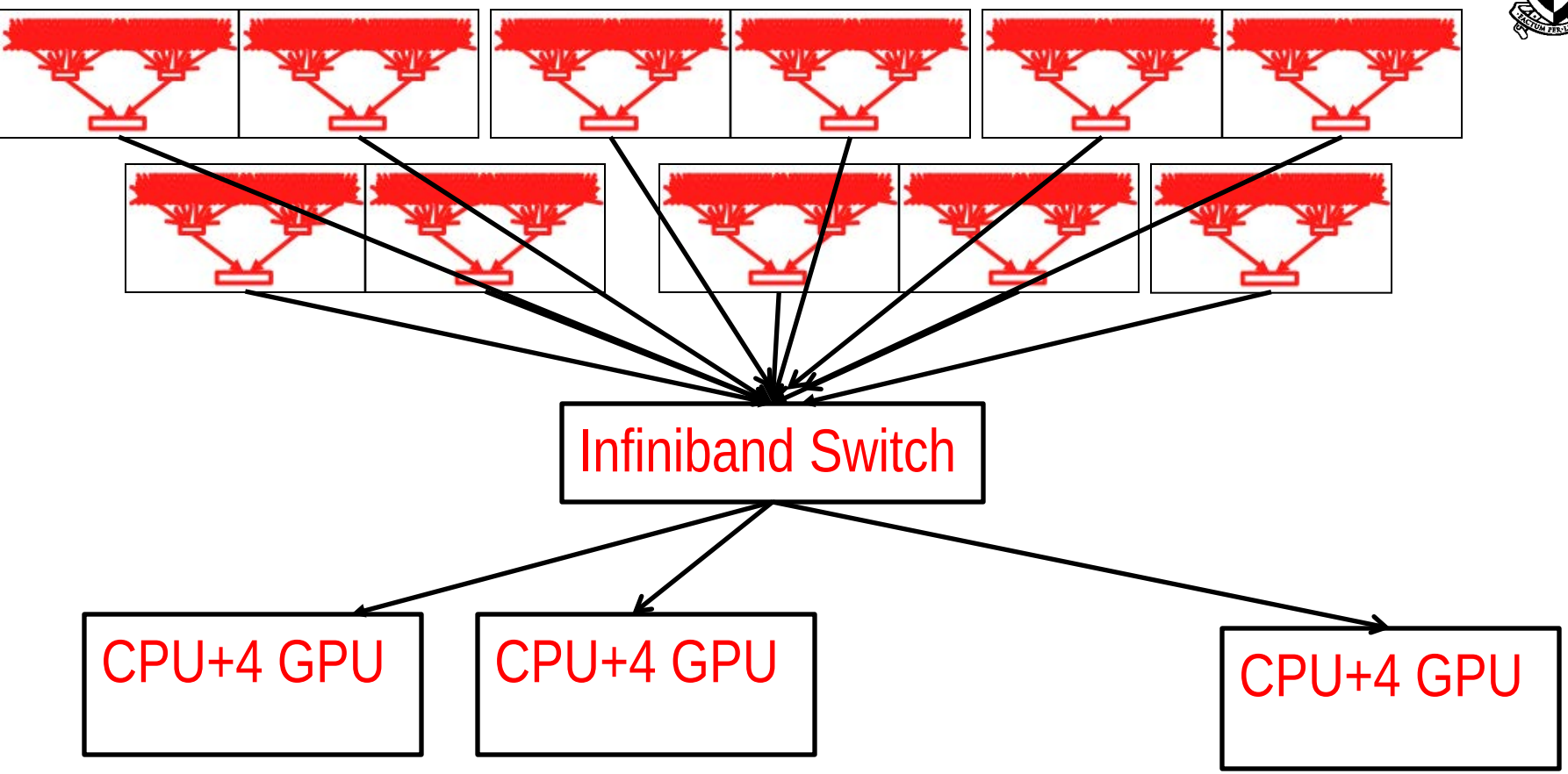


Millisecond pulsar (Johnston et al 1993)!



1 % of the telescope in use!

New Design (dual 10Gb NIC)



6 quad-GPU servers

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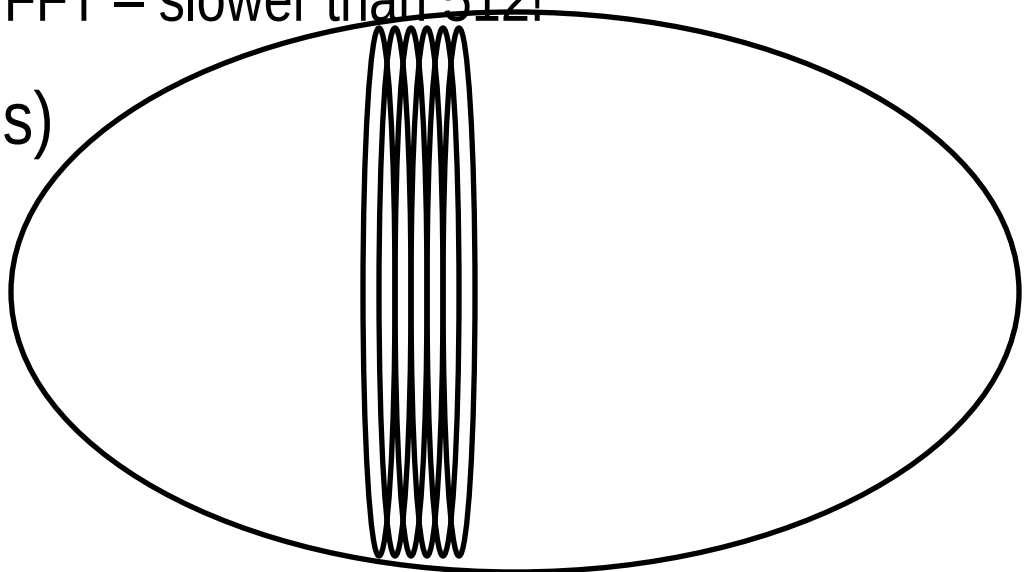
Interesting bits

- GPUs for RFI excision & incoherent folding
- RDMA over IB to do the corner turn (no CPU)
  - 4445 MB/s = 35.6 Gb/s
- 2D FFT to create 512 fan beams + finer channels
  - Whole instrument on 7 x 690s
  - Don't try a 352 point FFT – slower than 512!
- Raw dump mode (30 s)
  - RFI "parallax"



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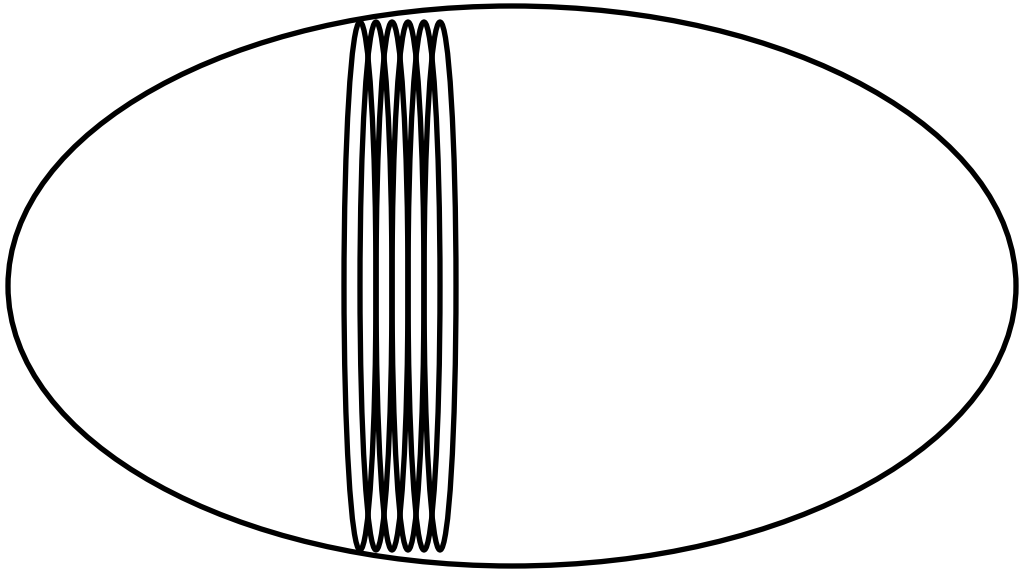
“Burst” mode

- Search fan beams for Lorimer bursts (FRBs)
- GPU dedisperser + “Heimdall”
  - Barsdell’s PhD thesis.
- Also find RRATs, single pulses from pulsars
- (Should) find 1 burst per 2 days > 10 sigma
- Real-time detector
- Raw dump from ring buffer
- Position 43”/SNR & 2 deg



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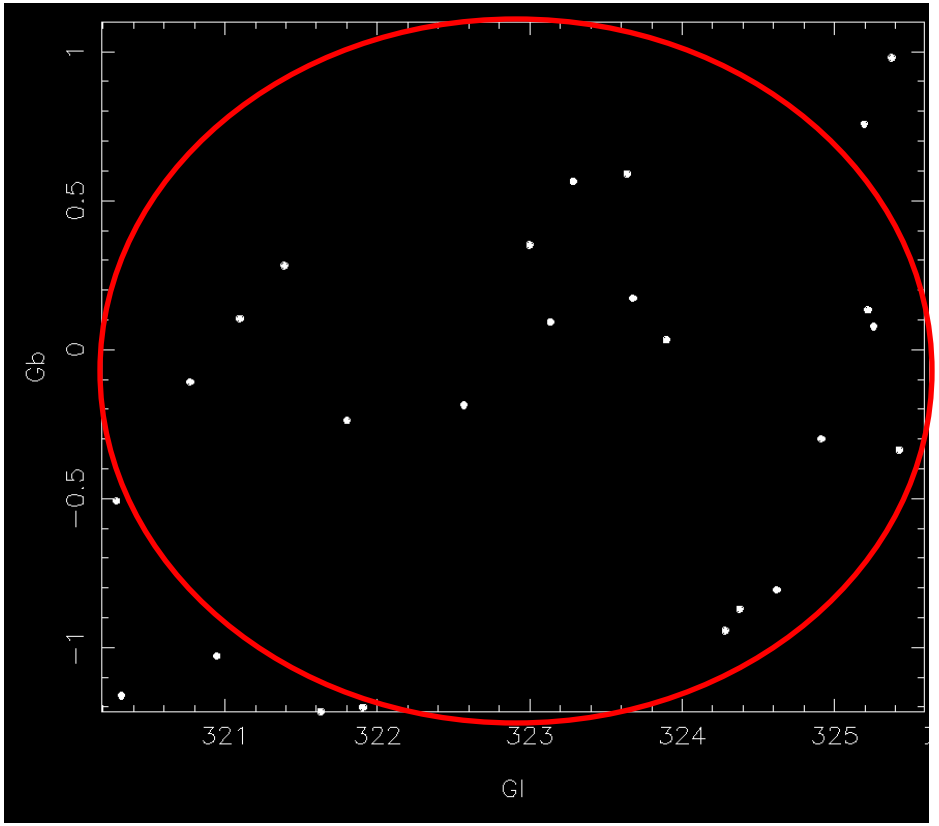
Fold fan-beam mode

- Coherently dedisperse any pulsar in the beam.
- Up to ~30 pulsars in one beam
- Time > 500 pulsars/day



New system vs old MOST system

- 4 x FoV
- 10 x Bandwidth
- 256 us timescale RFI monitor & excision
- 512 fan beams vs 96 or FX mode
- 15,000 spectral channels vs 1
- Multiple pulsar coherent dedispersion vs 1x3 MHz channel, one pulsar system
- *Simultaneous burst, mapping, pulsar mode, RFI excision modes using 33 dual-GPUs.*

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Timeline

- This week – installation of 20 RX boards!
  - Enough for 80 modules!
  - Can tie 4 modules “in analogue” and get up to 22x4x4=352
- T+?
  - Tim Bateman to redo PFB
  - Stage 1: Two good -> four good channels (trivial?)
  - Stage 2: Four good -> Twelve good channels (weeks?)
  - Stage 3: Twelve good -> Sixteen good channels (more weeks?)
- Rest is CPU/GPU software.