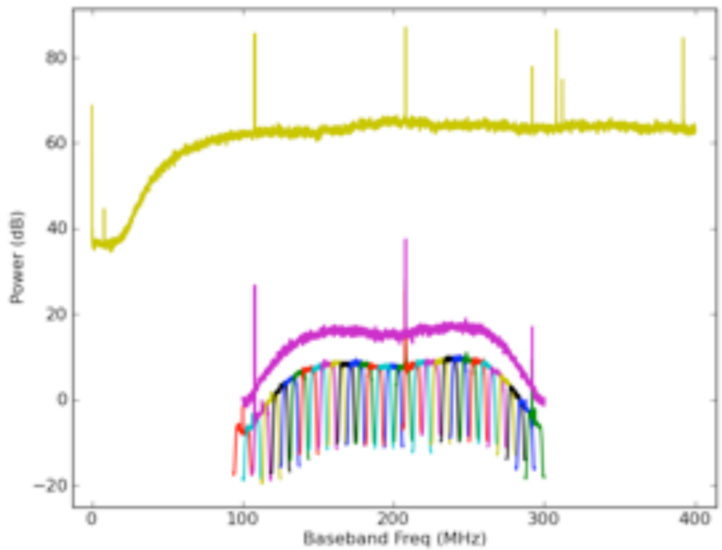
Instrumentation for real-time cyclic spectroscopy



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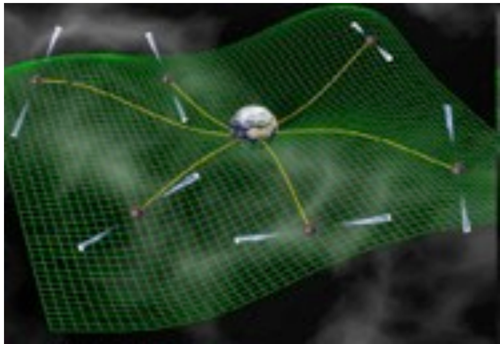
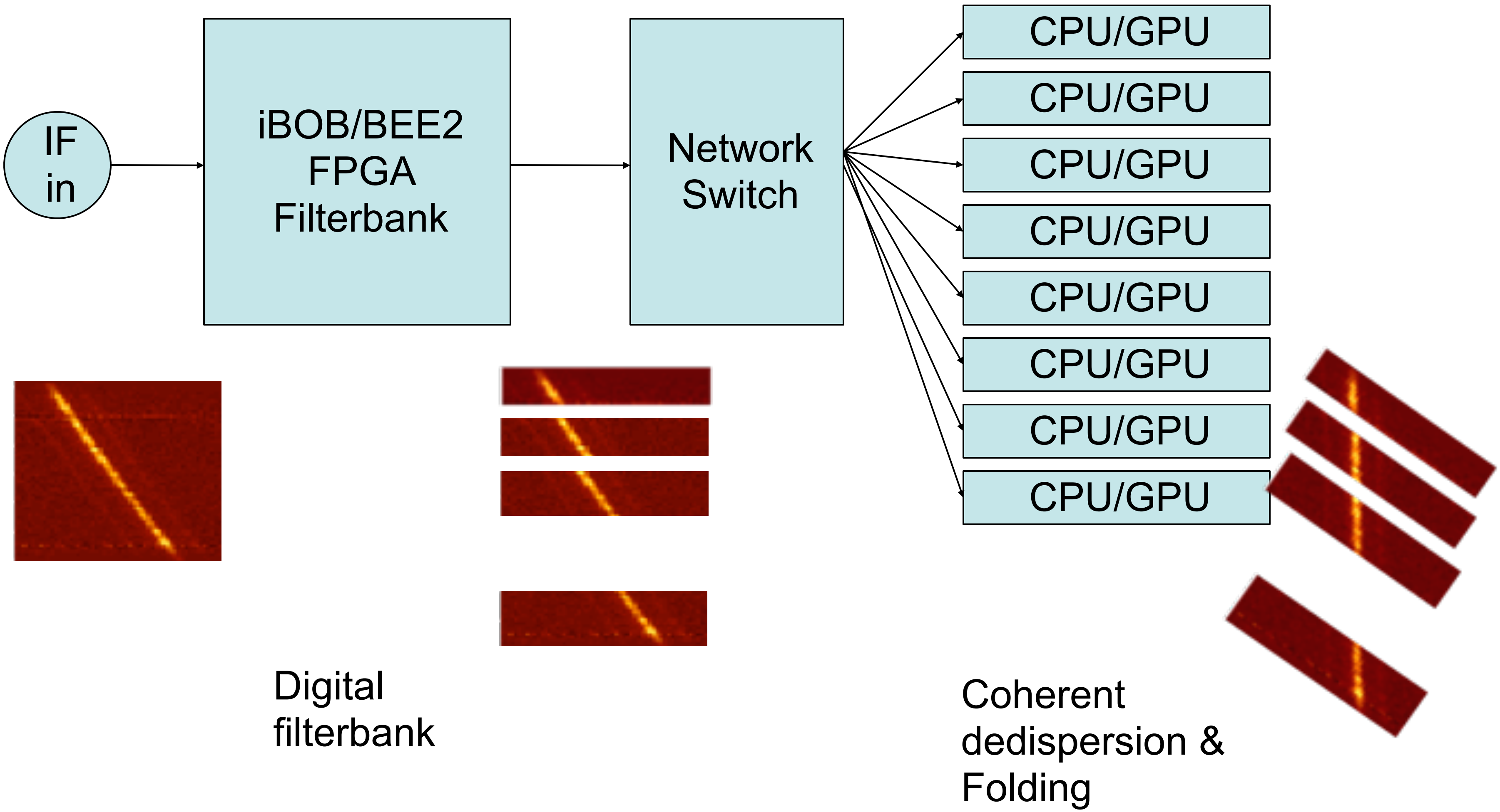
Motivation: Improving pulsar timing

- At frequencies below ~1 GHz, pulsar time of arrival estimation is strongly influenced by scattering in the interstellar medium
- PTAs need more pulsars which can be accurately timed
- Hopefully CS will enable a large number of MSPs which are bright but scattered at low frequencies to be included in the PTA
- Also hope to improve best timers to ~10 ns RMS

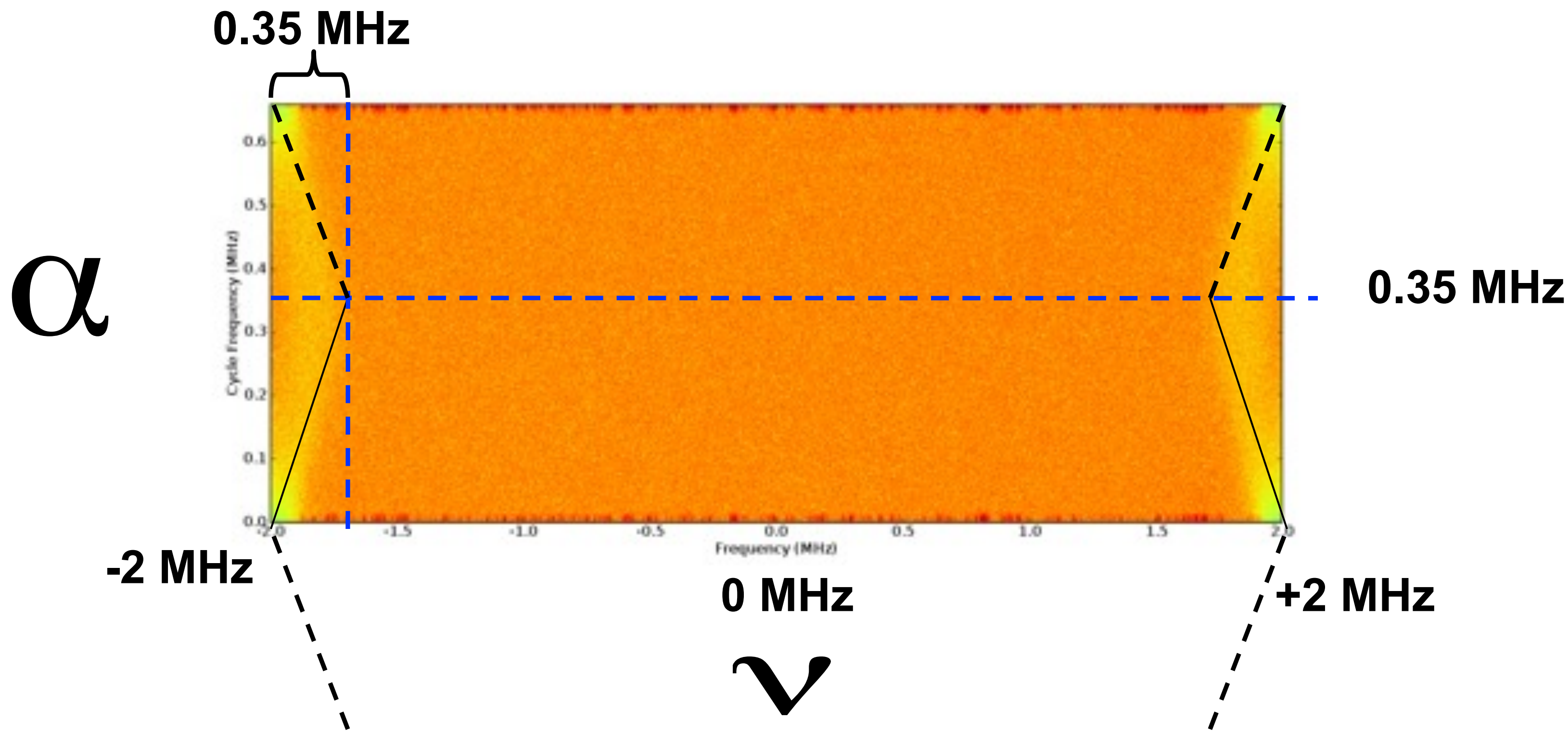


Modern pulsar processor review: G/PUPPI Architecture



Cyclic Spectrum:
Edge effects

$$S_x(\nu;\alpha) = E\left\{X(\nu+\alpha/2)X^*(\nu-\alpha/2)\right\}$$

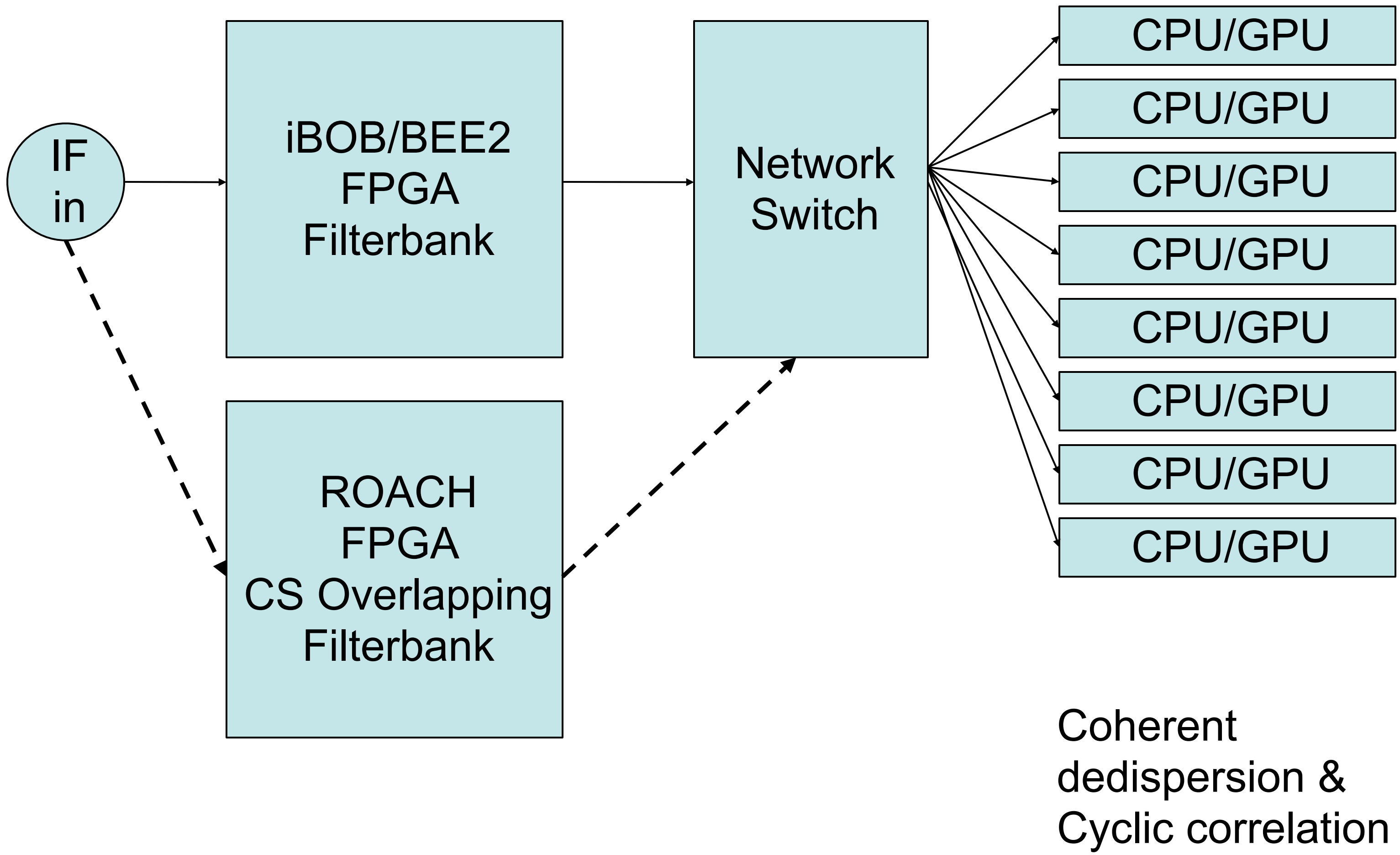


$$|\alpha/2| + |\nu| < B/2$$

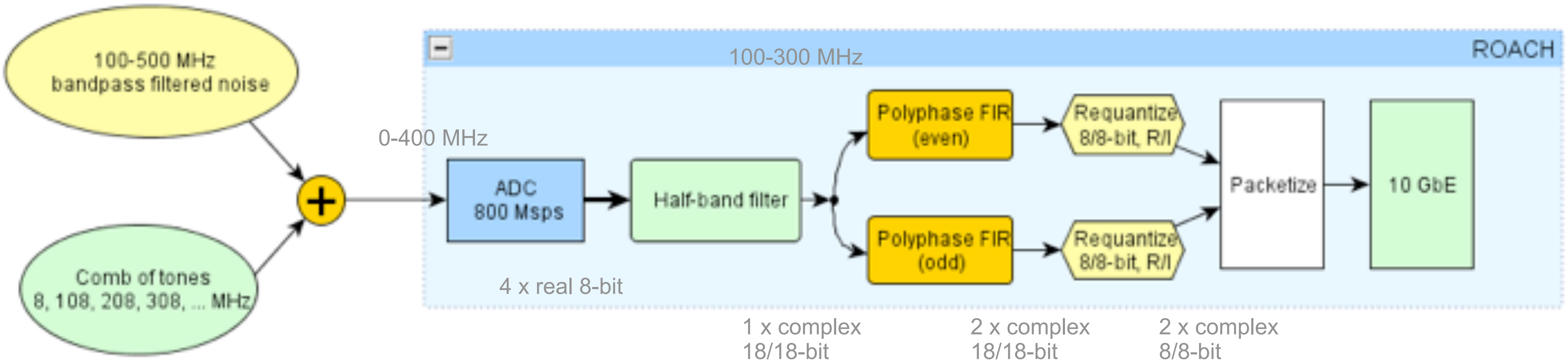
Computing Cyclic Spectrum in Real-time

- Processing a single band results in edge effects
  - Need to overlap bands
- Why not send whole (~1 GHz) band to GPUs to do everything?
  - Hard to distribute data, need long chunks of contiguous data, lots of buffering
- Simplest approach: **filterbank with overlapping channels**

Adding CS Front-end to G/ PUPPI

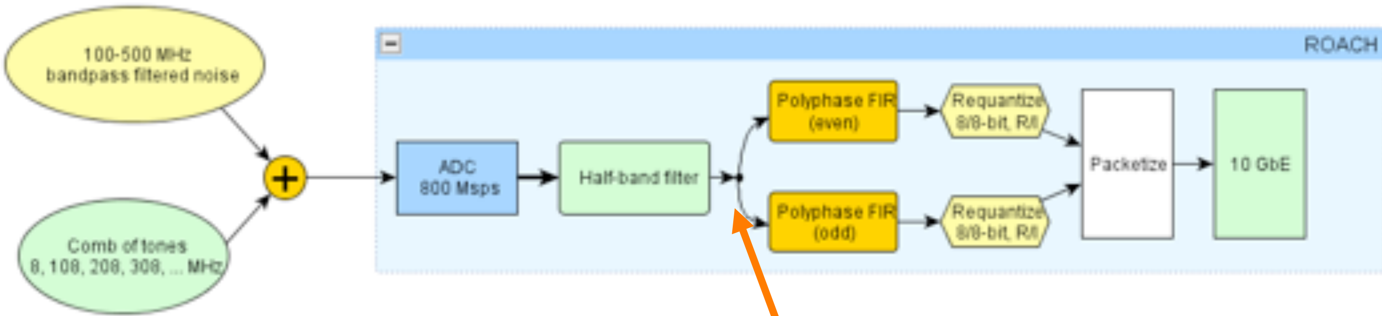


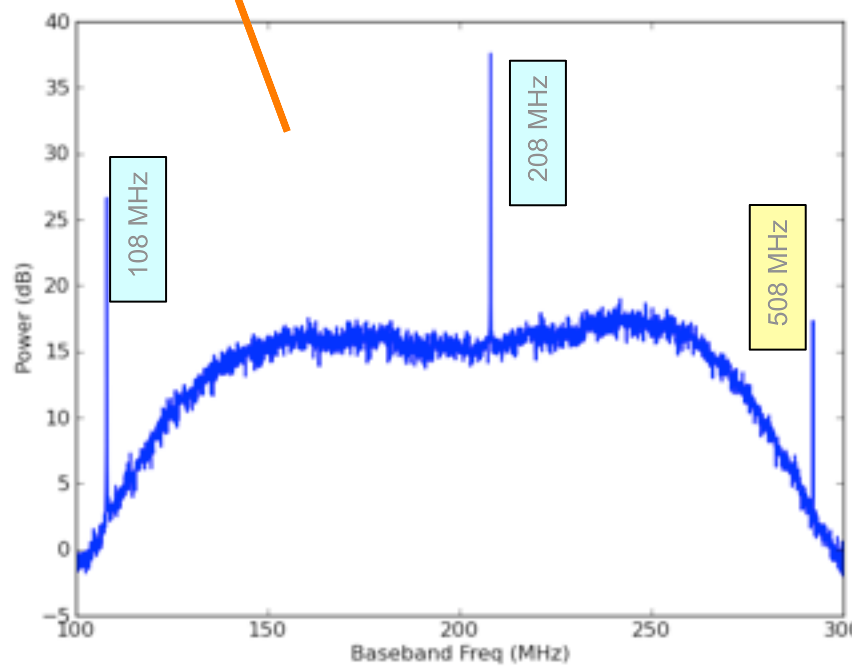
Initial ROACH design



- Uses Half-band filter to provide single complex data stream at 200 MHz for simplicity
- Overlapping channels requires processing the data with two polyphase filterbanks in parallel
- Dual polarization

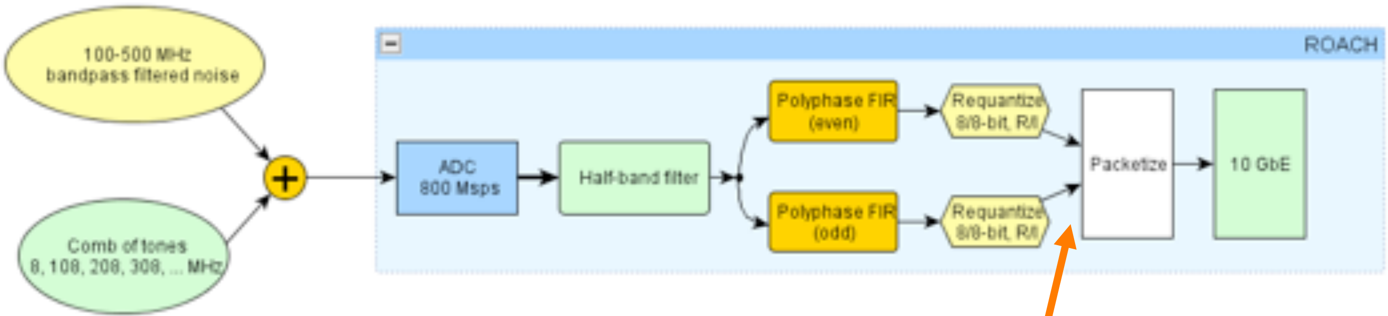
Output of Half-band Filter: 100-300 MHz

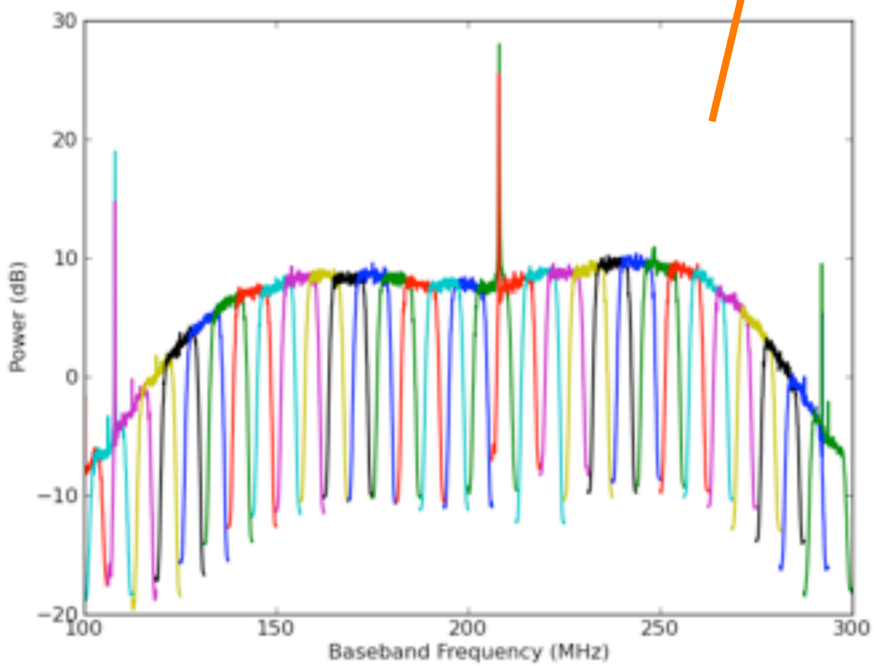




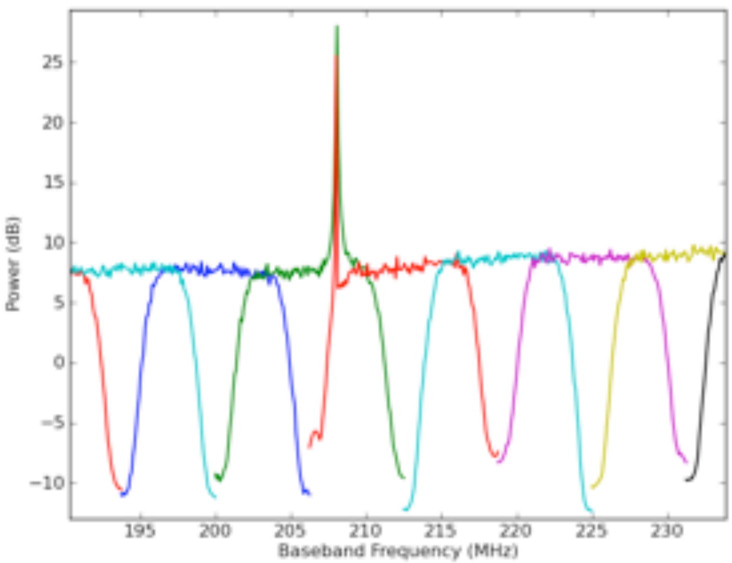
- Note: Filter response was purposefully chosen to help verify functionality (by being able to see the skirts
- Filter is built of digital mixer at pi/2 and 32-tap decimating FIR filter

Final output



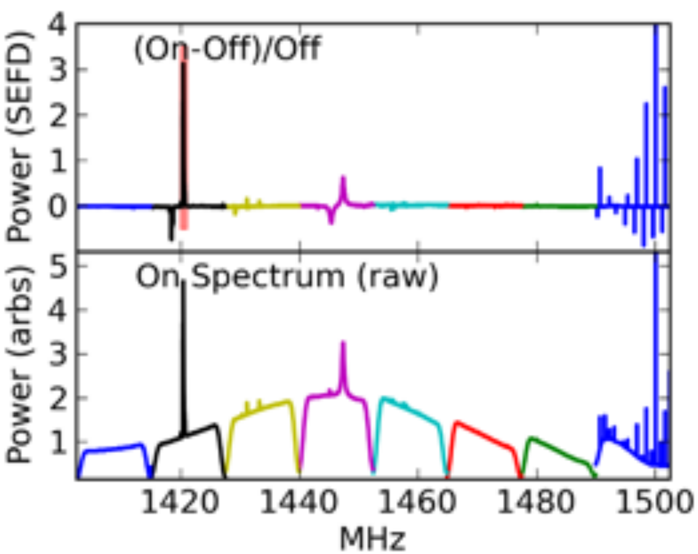


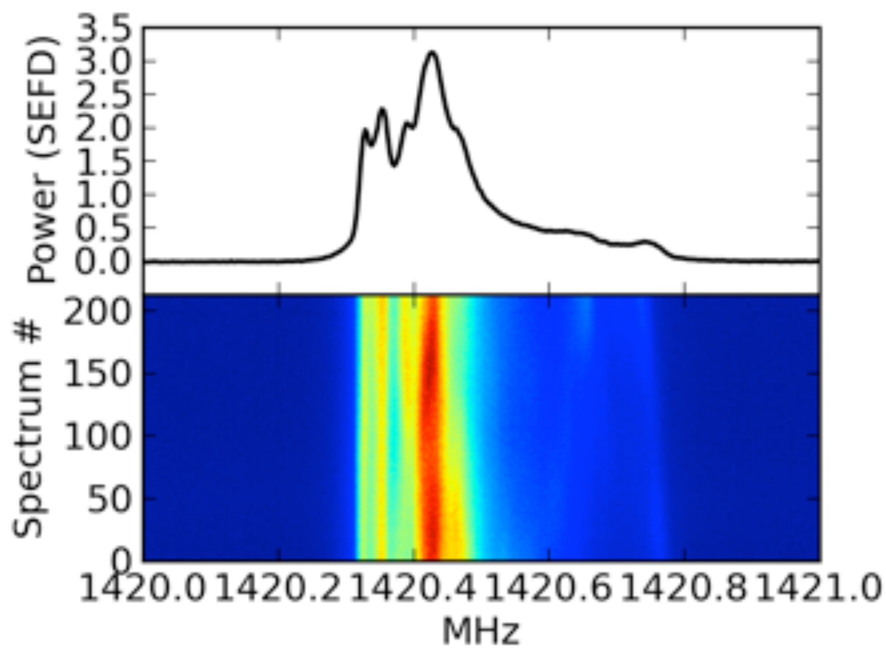
Zoom in on channel response



- 32 channels across 200 MHz → 6.25 MHz spacing
- Sample rate for each channel is 12.5 MHz (complex)
- Response is set at 1.5x to allow visualization of filter skirts

First light: That’s not a pulsar!

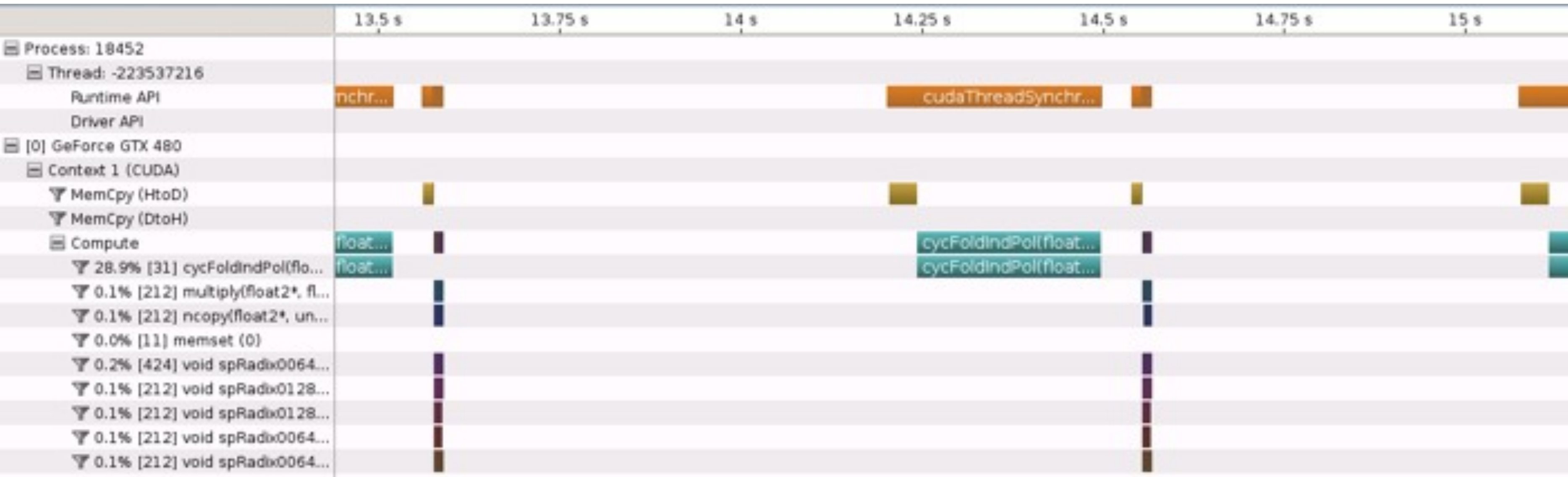




Test Data – courtesy of Nipuni

- J1713+0747
- 10 MHz baseband data
- Centered at 335 MHz
- Recorded at Arecibo
- DM ~16, p = 4.58 ms
- Tscattering expected to be ~ 1 us

-b 256 -F4:D -cyclic 1024 (513 lags)

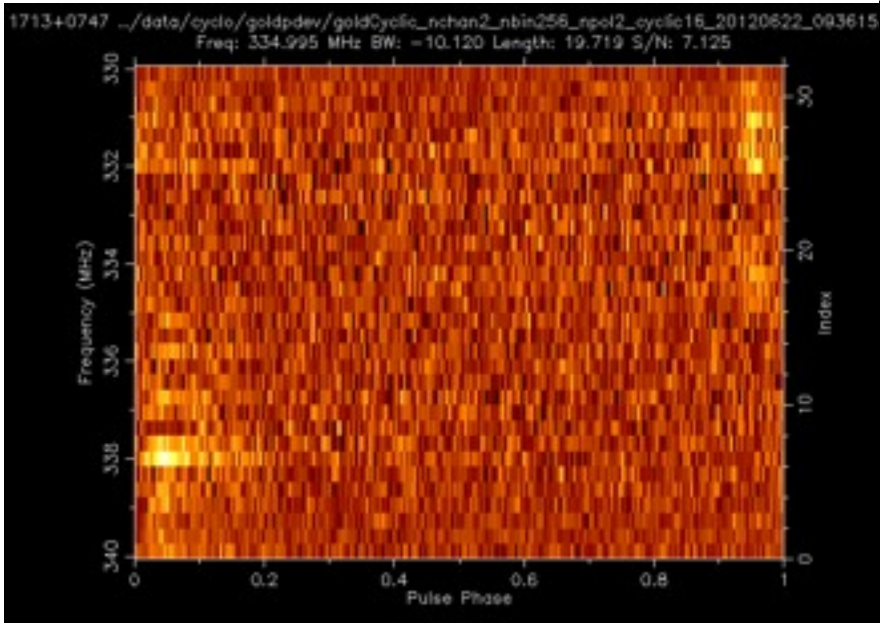


- Occupancy ~ 0.521
- Time is dominated by set_bins (12s vs 7s)
- 31 x 253ms

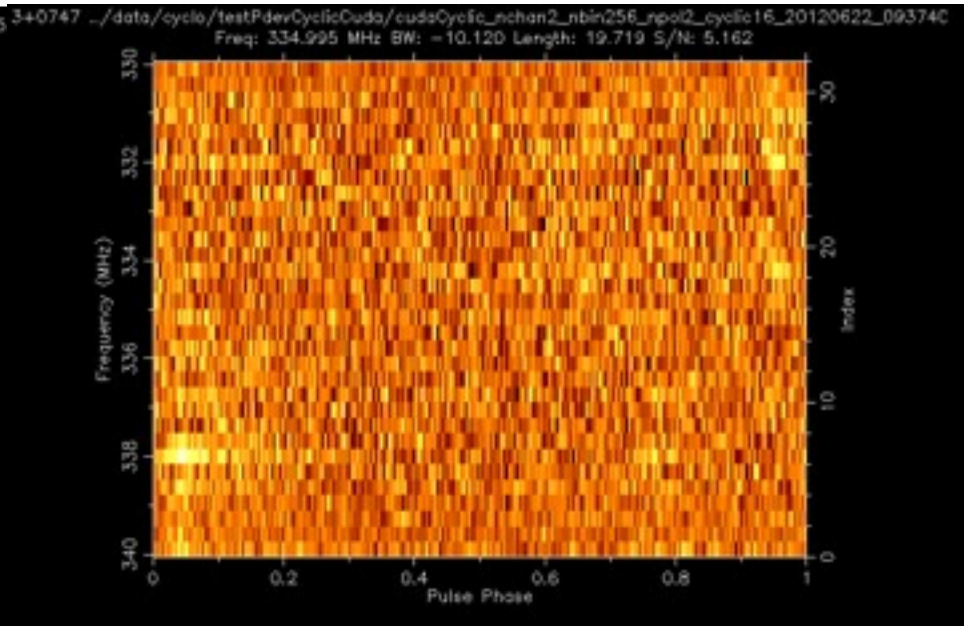
Some bug remains in GPU version

2 channels, 16 cyclic

CPU

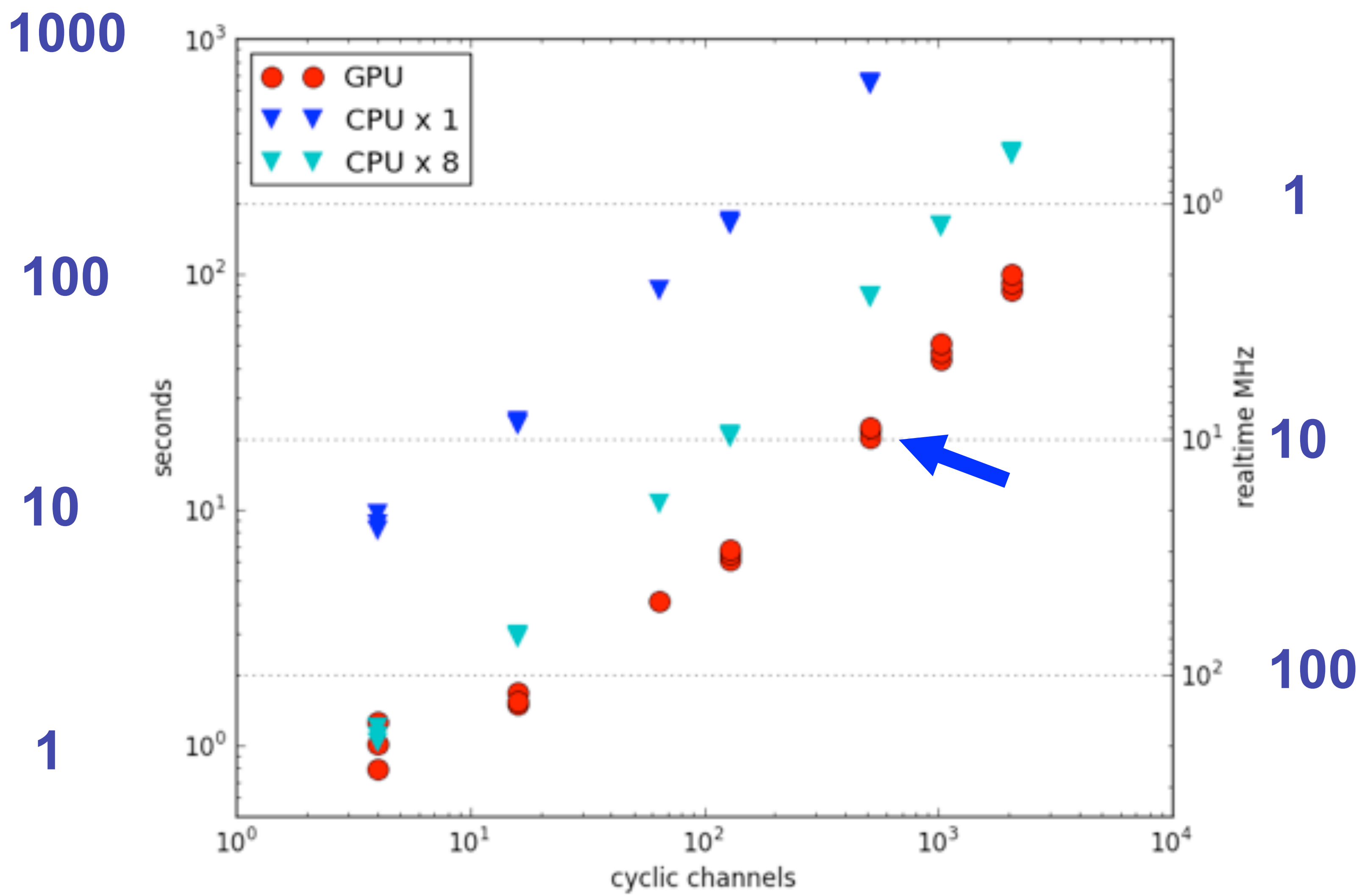


GPU

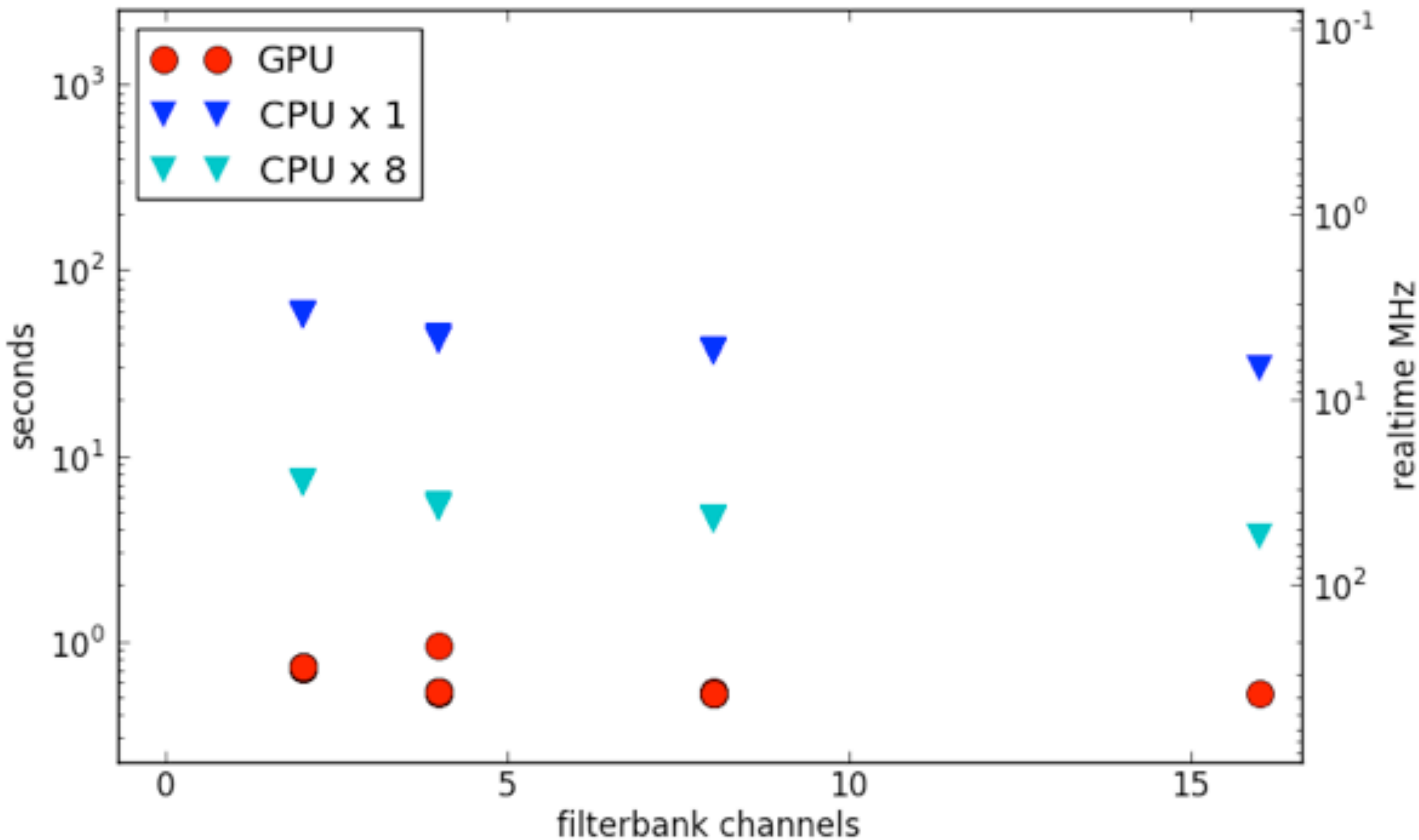


Current performance summary: 10-20 MHz per GPU node

GTX485



Coherent Dedispersion Filterbank (negligible in comparison)



Test plan – 6 hours at Arecibo

- Hardware is available (borrow the PUPPI GPUs)
- 2 x 1 hour on B1937+21 @ 430 MHz to make sure everything's working
- Science runs on B1953+29 and J2317+1439. For each:
  - 1 hour @ 327 MHz (312-342 MHz)
  - 1 hour @ 430 MHz (422-442 MHz)
  - 1 hour @ 1400 MHz
- **Planning to propose for GBT time in next cycle; brand new GPU cluster will be available.**

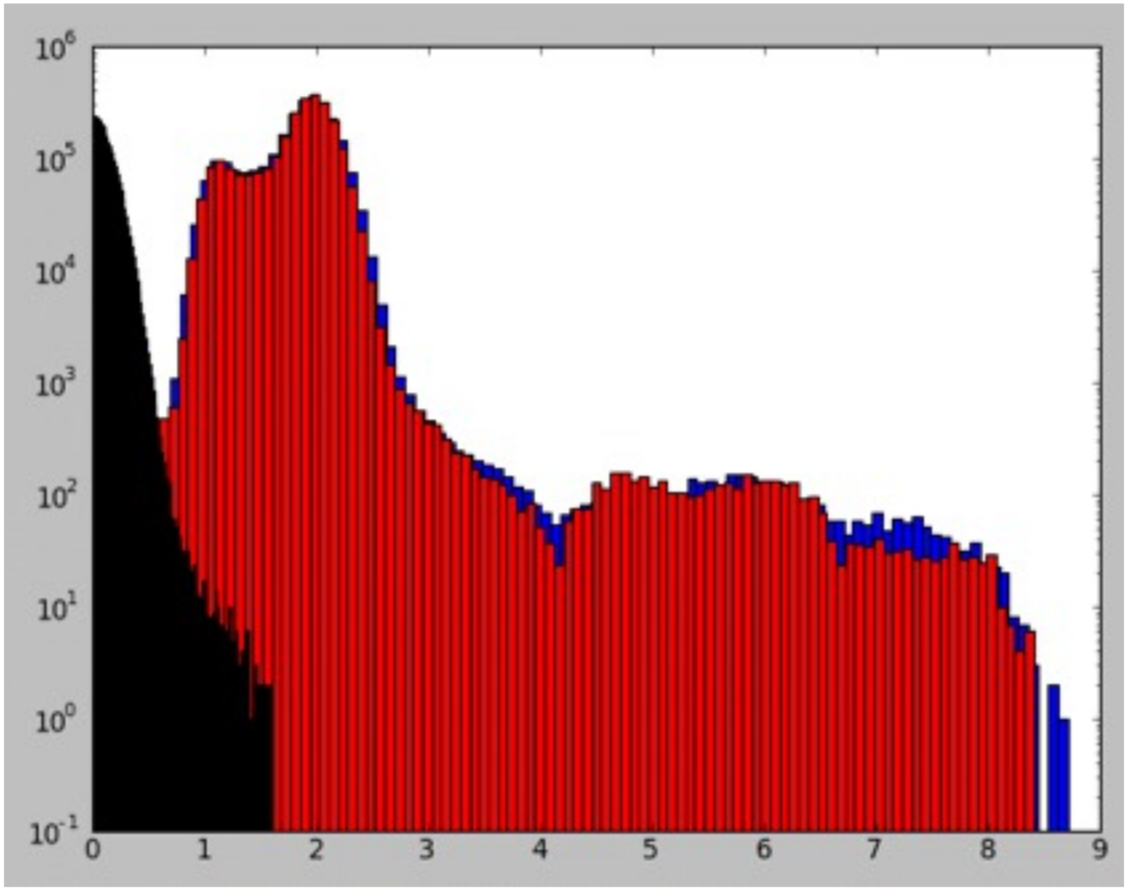
References

- P. B. Demorest. “Cyclic spectral analysis of radio pulsars.” MNRAS 416 2821. Arxiv: 1106.3345
- Images from http://www.cv.nrao.edu/~pdemores/cyclic/
- Crochier & Rabiner. “Multirate Digital Signal Processing.” Prentice-Hall. 1983

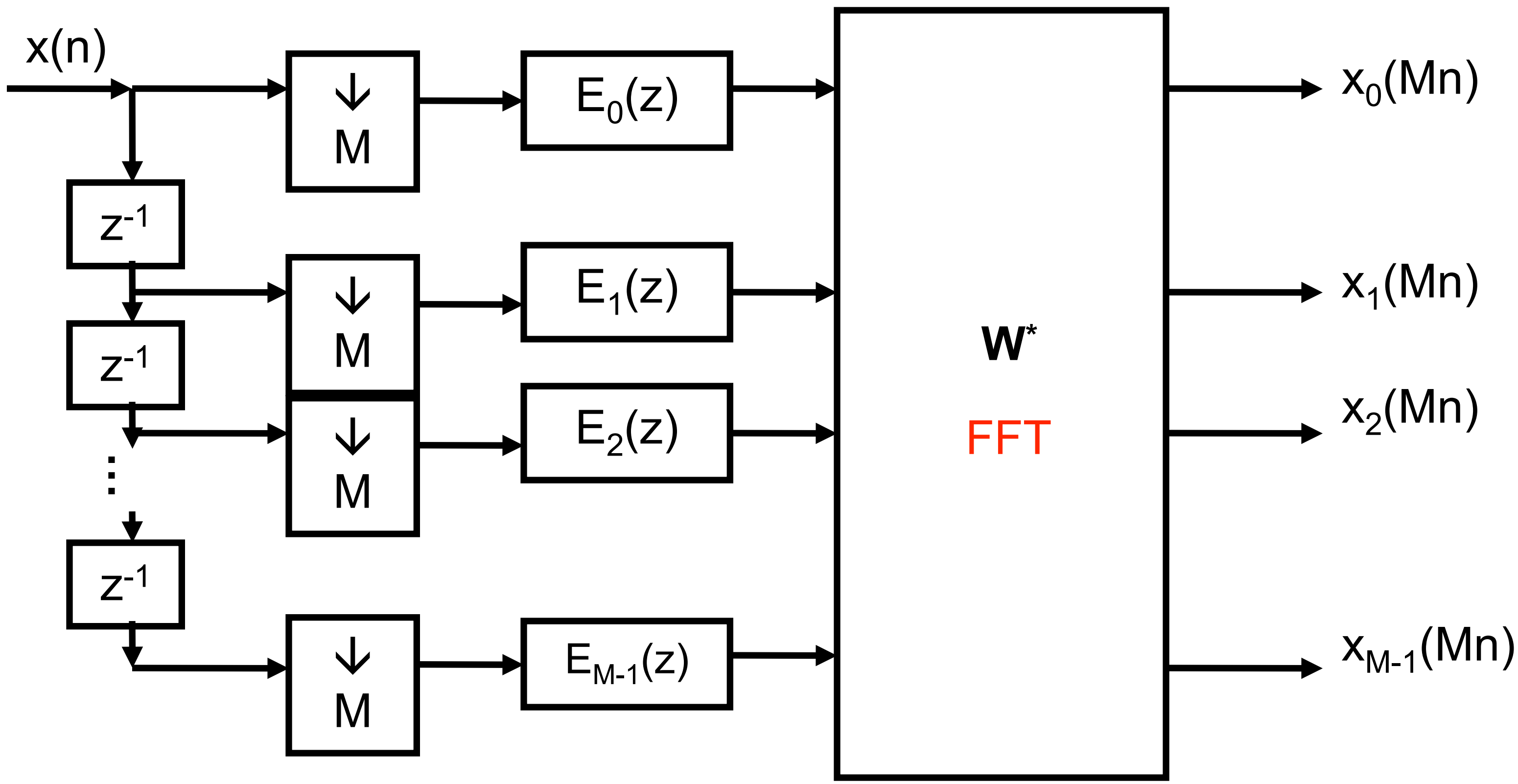
Pulse Scattering

- Broadens pulse features → reduces time resolution
- Varies from observation to observation → increases timing noise
- Strongly frequency dependant → observations are done at higher frequencies
  - But pulsars are steep spectrum, so there is a tradeoff
- Ideal solution would be to correct for scattering

Data and Error distributions

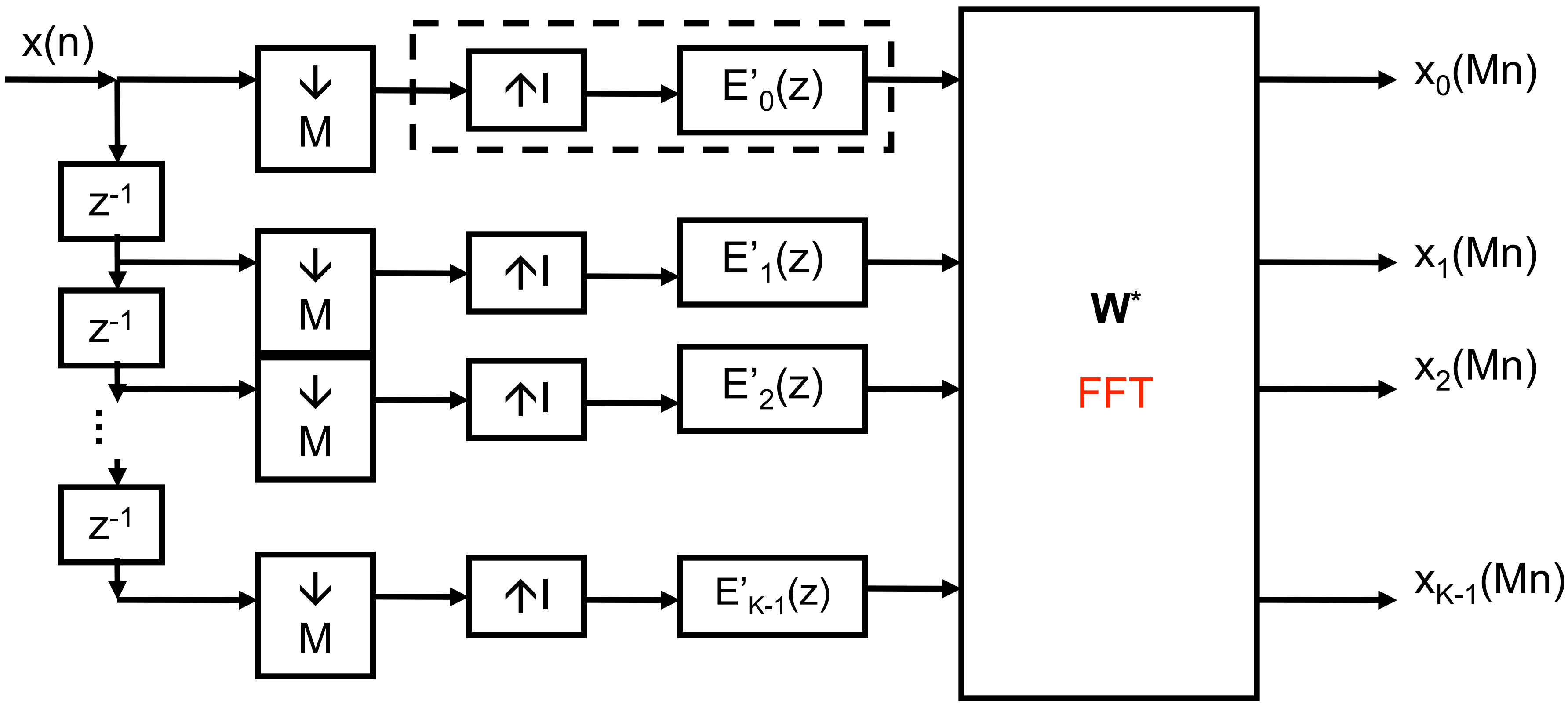


Critically Sampled Filterbank: Data rate in (F) = data rate out (F/M)*M



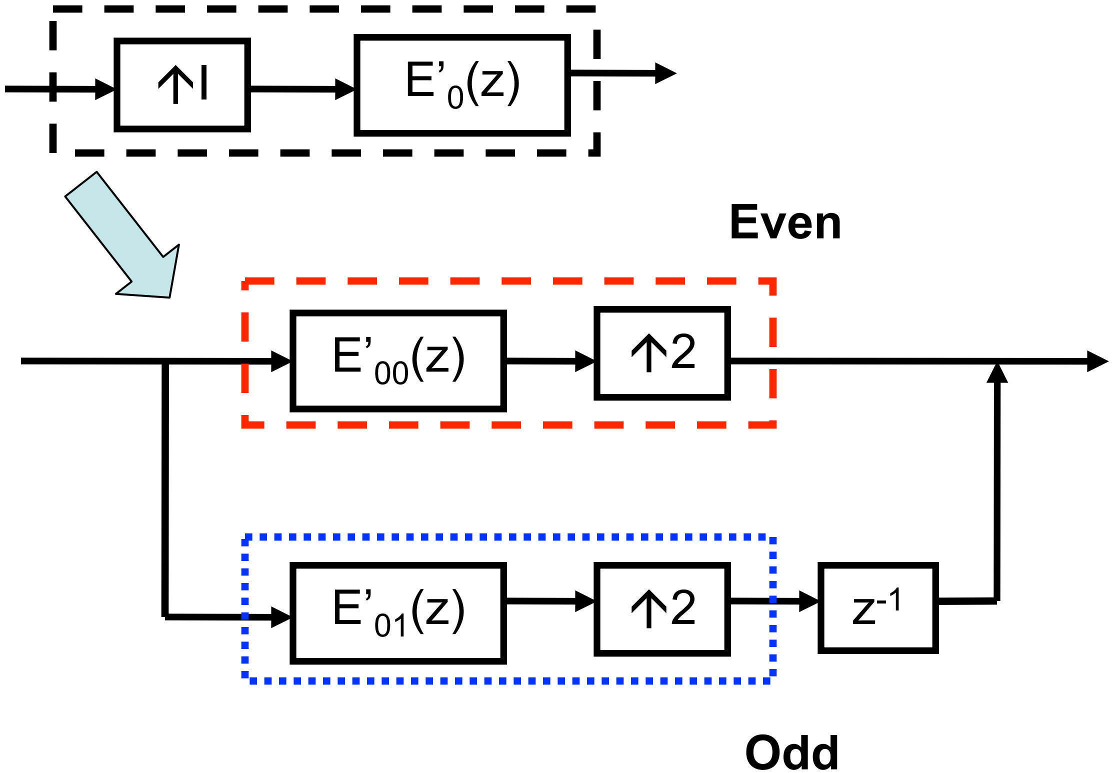
Over-Sampled Filterbank:

Data rate in (F) ≠ data rate out (F/M)*M*I



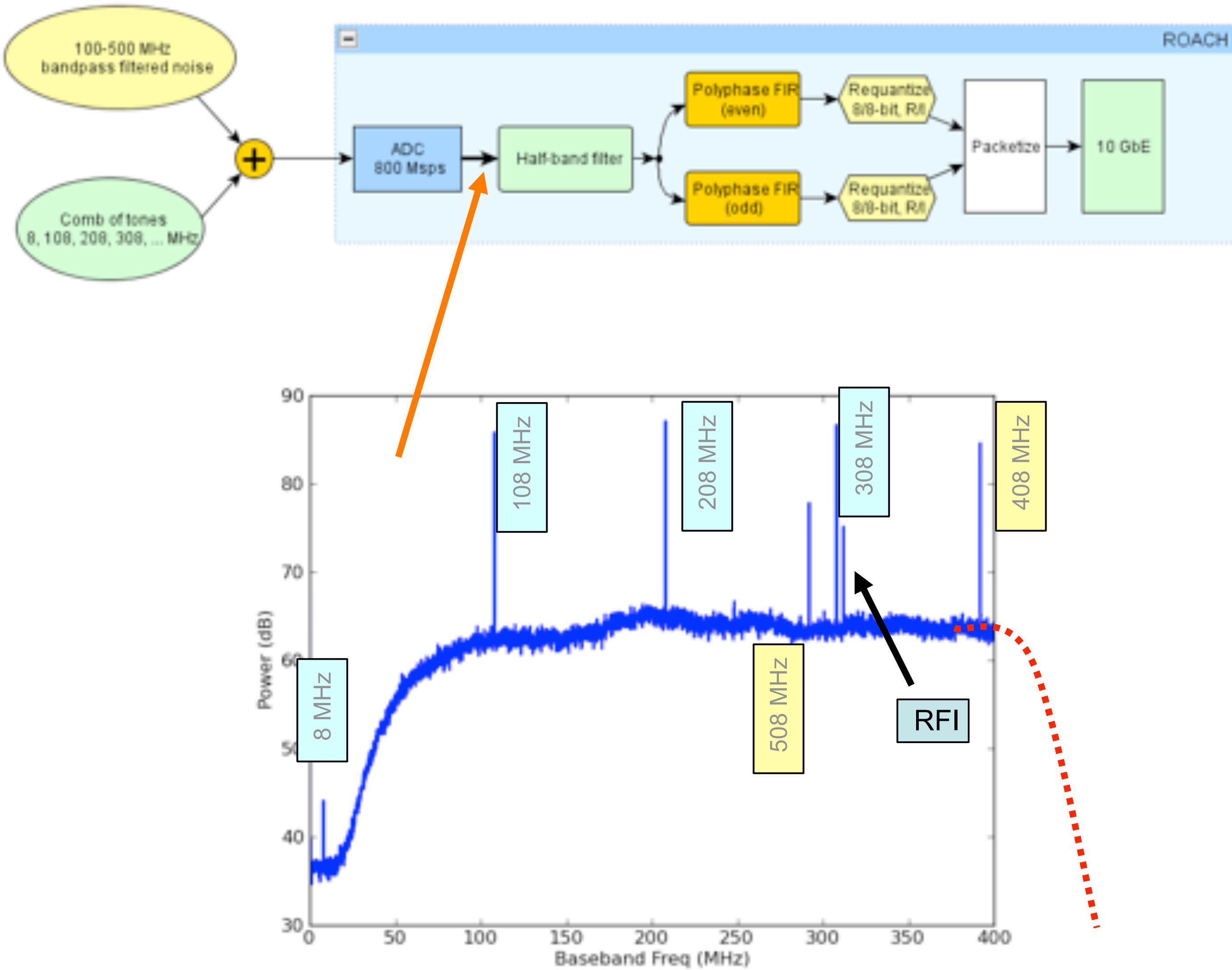
Over-sampled filterbank

$K = M{*}I, \quad I=2$



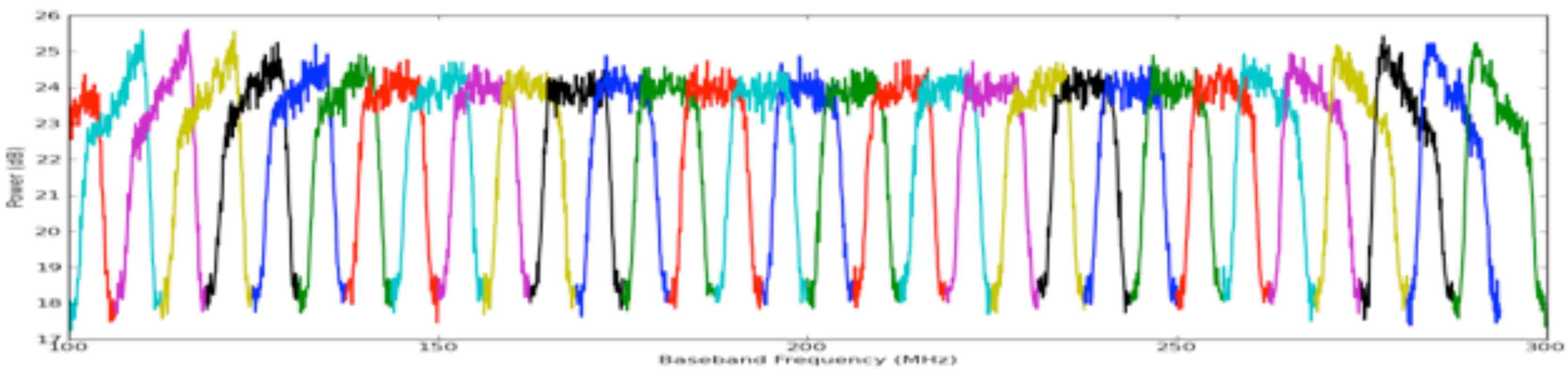
"the polyphase filters of the polyphase filters"

ADC input spectrum: 0-400 MHz

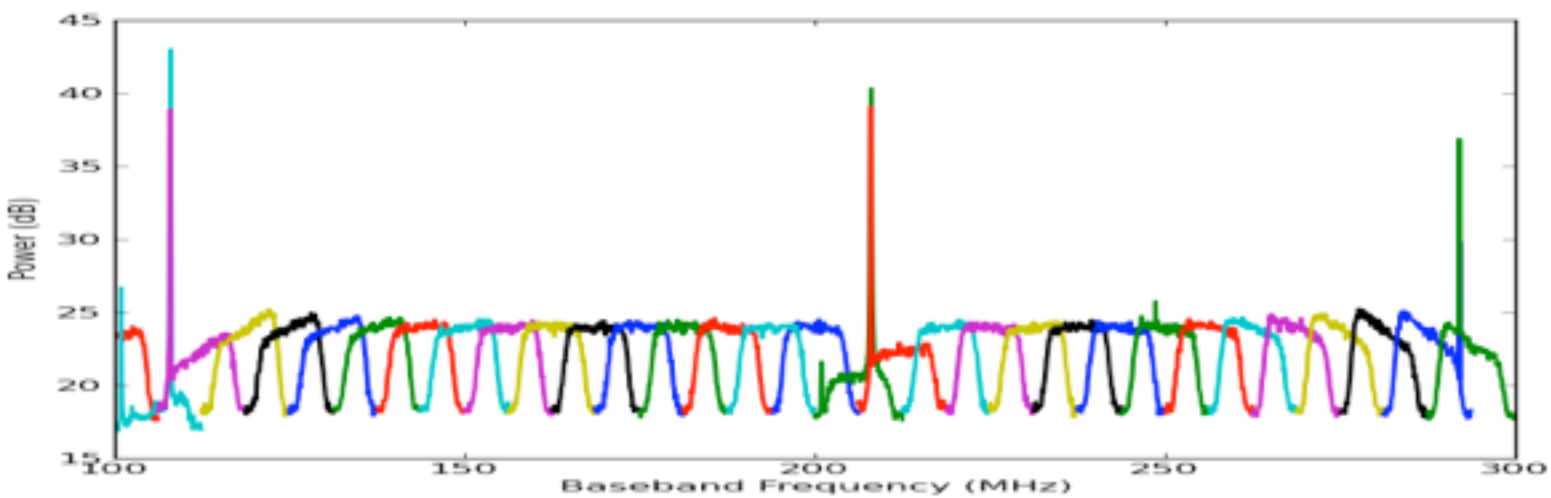


After Equalization

Comb Off



Comb On

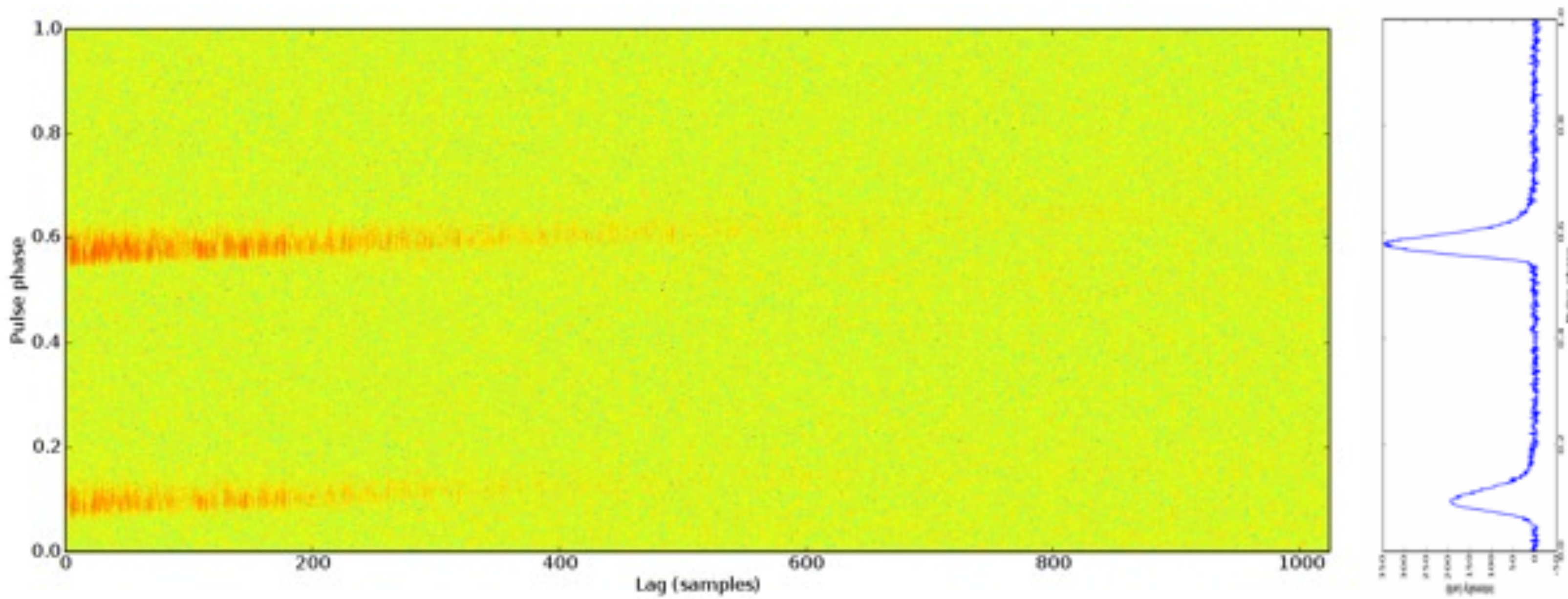


Cyclic Correlation:
Correlation averaged modulo pulse period

$$C_x(t,\tau) = E\left\{x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})\right\}$$

t

~1470 us

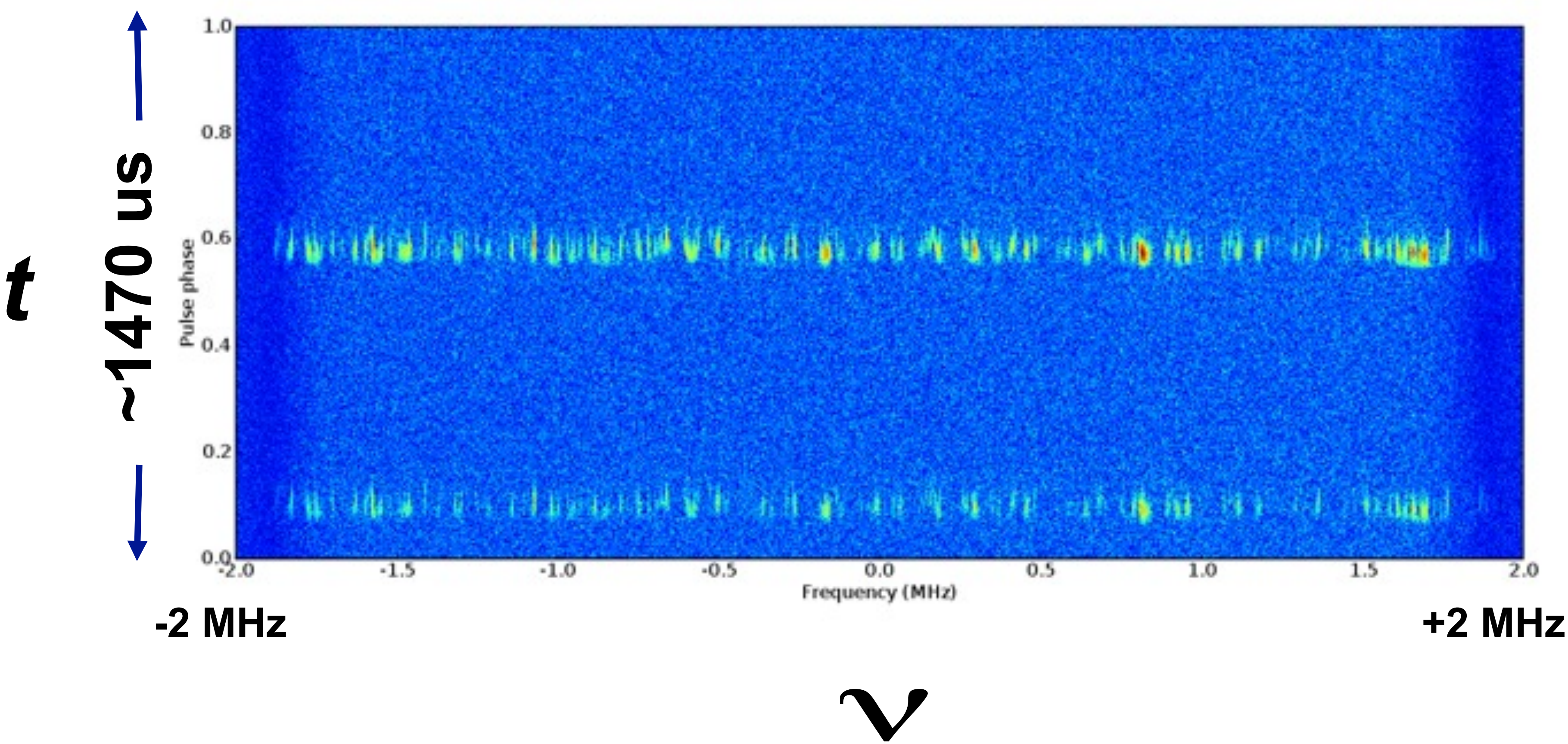


256 us

τ

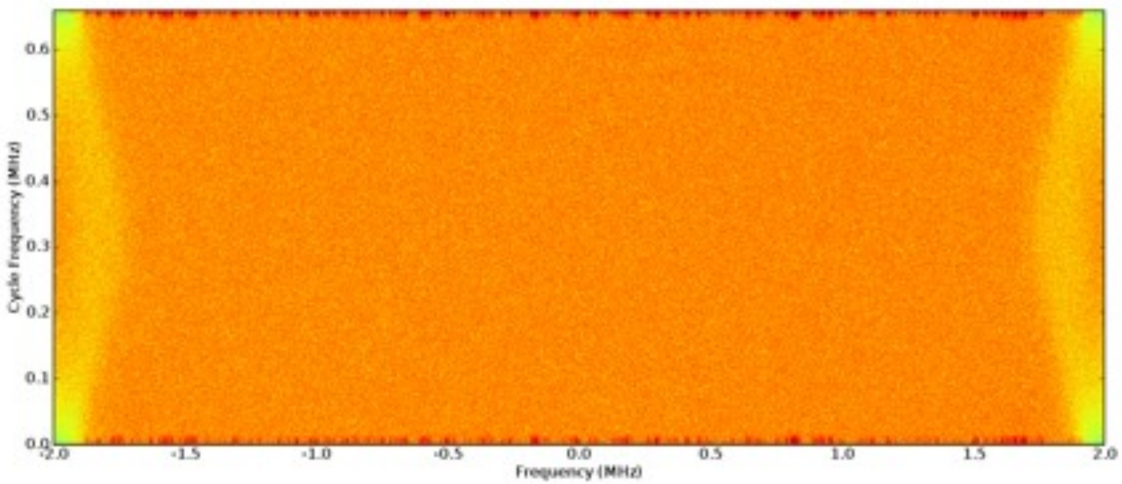
Periodic Spectrum:
Fourier transform along tau axis

$$S_x(\nu, t)$$



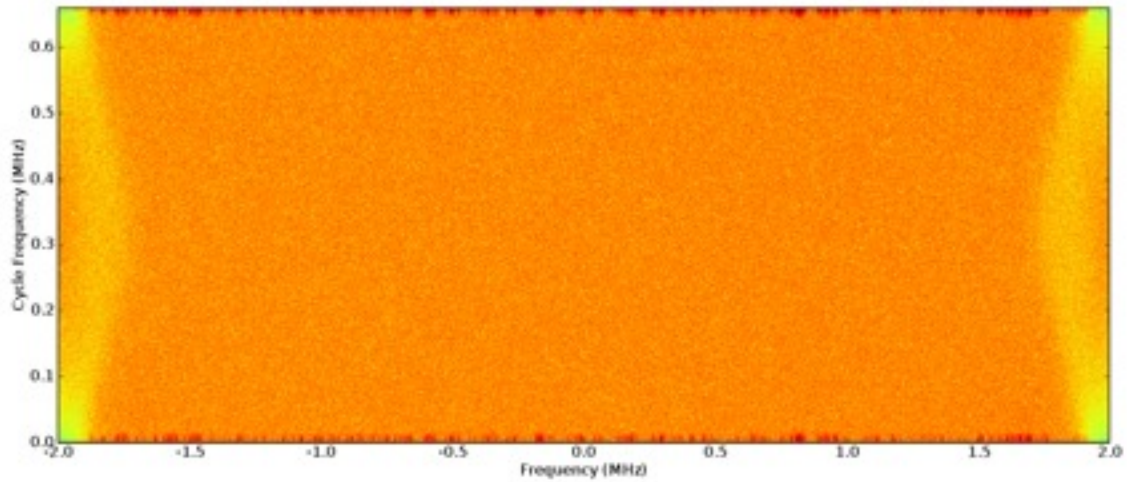
Cyclic Spectrum:
Fourier transform along t and tau axes

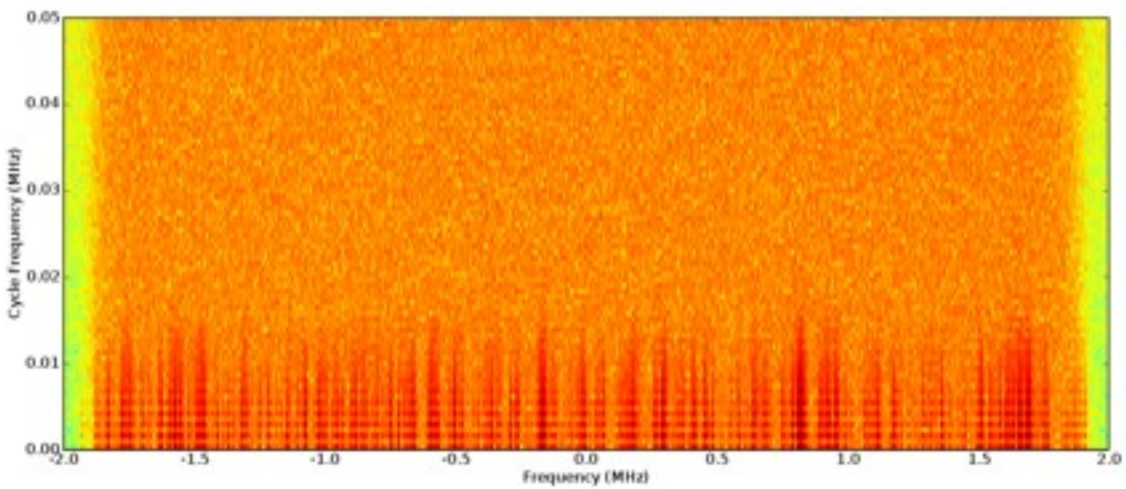
$$S_x(\nu;\alpha)$$



Cyclic Spectrum:
Fourier transform along t and tau axes

$$S_x(\nu; \alpha)$$





Traditional spectrum of filtered noise: Only magnitude is retained

ISM scattering

Observed signal

Original pulsar signal

$$y(t) = h(t) \star x(t)$$

$$Y(\nu) = H(\nu)X(\nu)$$

$$S_y(\nu) = \left|H(\nu)\right|^2 S_x(\nu)$$

Cyclic spectrum of filtered noise: Phase information can be retrieved

Observed signal

ISM scattering

Original pulsar signal

$$y(t) = h(t) \star x(t)$$

$$Y(\nu) = H(\nu)X(\nu)$$

$$S_y(\nu;\alpha) = H(\nu + \alpha/2)H^*(\nu - \alpha/2)S_x(\nu;\alpha)$$

$$S_y(\nu;\alpha_n) = H_{ISM}(\nu + \frac{\alpha_n}{2})H^*_{ISM}(\nu - \frac{\alpha_n}{2})I(n)S_0$$