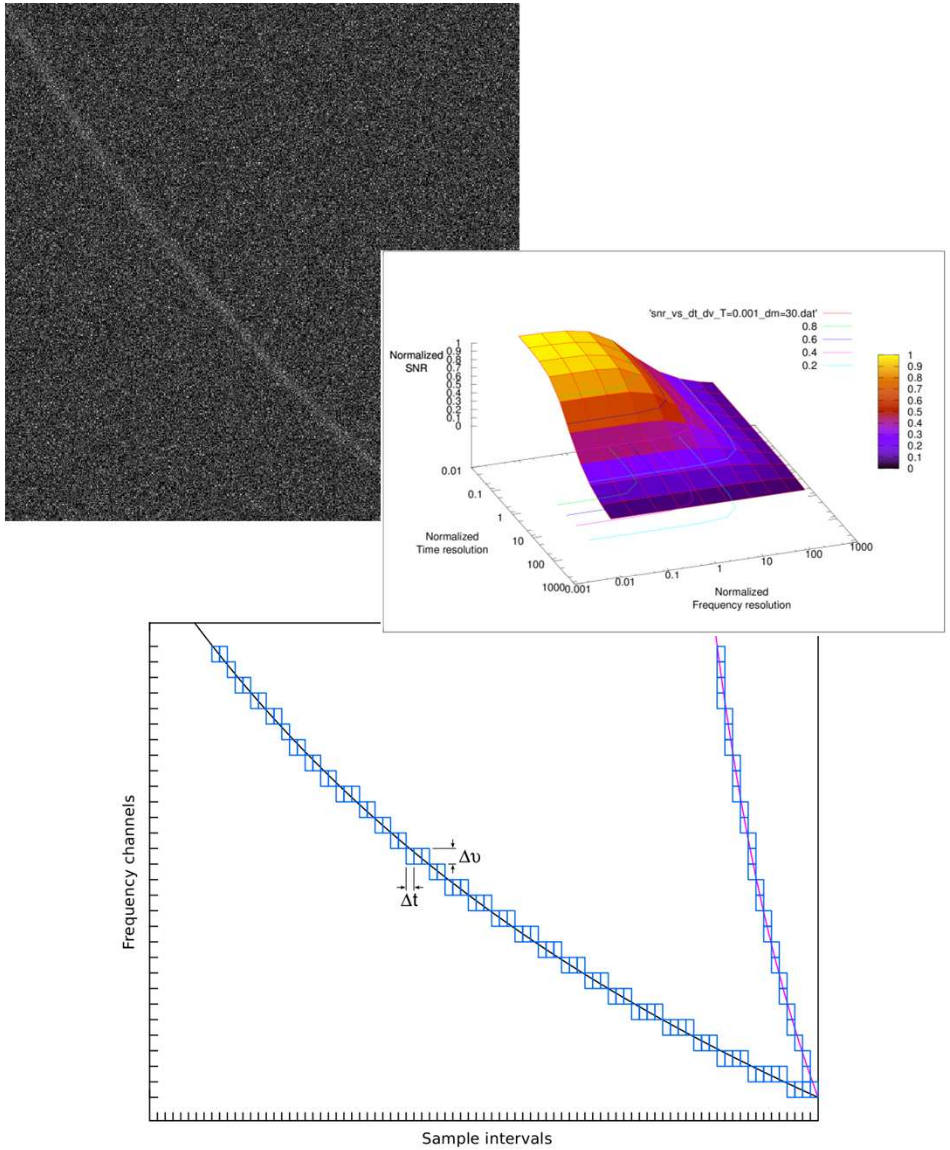
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS



Design and performance of fast transient detectors

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Outline

- The incoherent detector
  - The classical matched filter – pros and cons
  - Degrading effects – scattering, inaccurate de-dispersion, trial templates
  - Performance for high DM events, at different frequencies

- How to design a better detector?
  - CRAFT detector – working with the dynamic spectrum
  - Fitting into the hierarchy and implementation
  - Asymptotic performance

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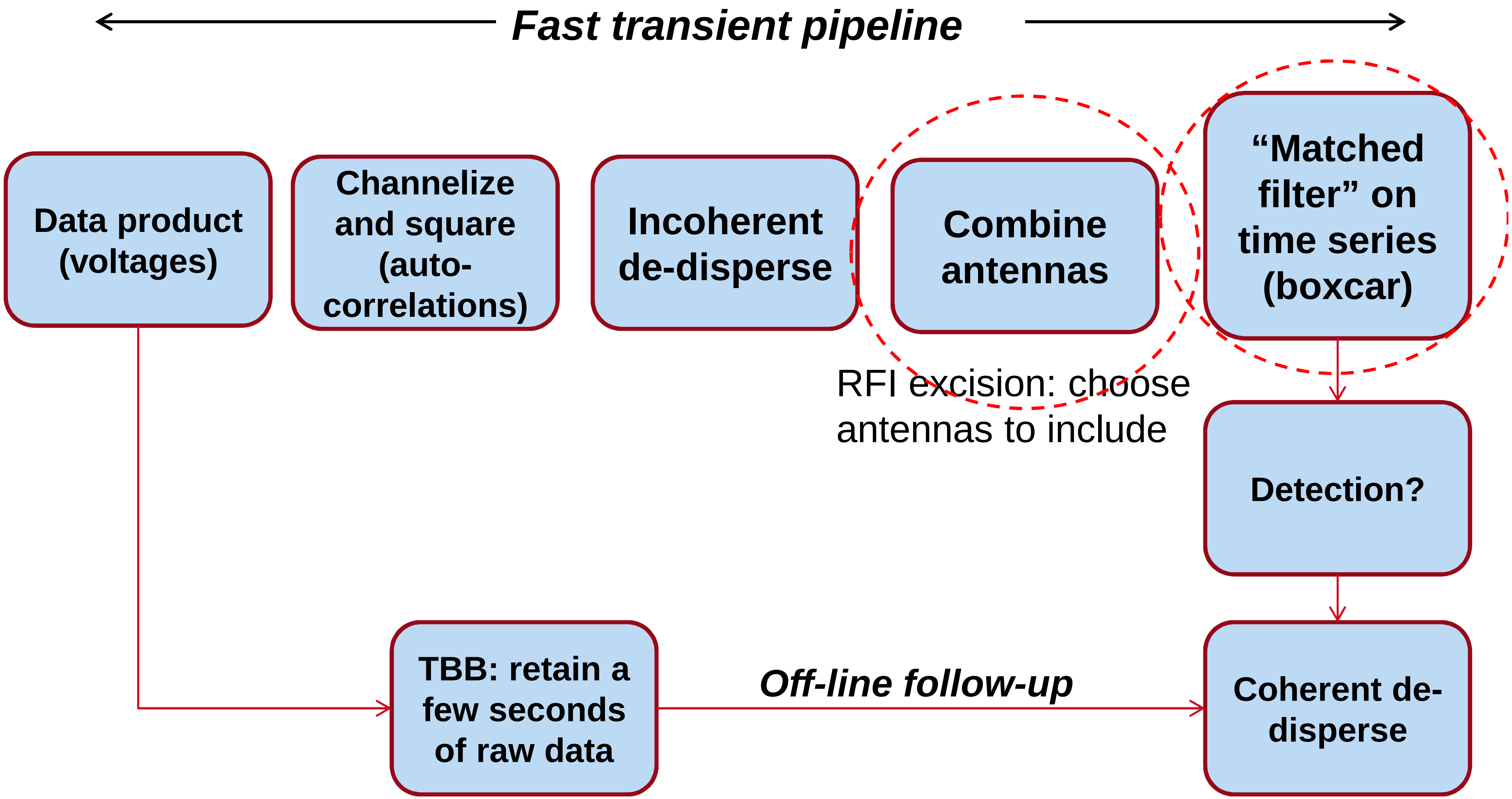
Fast transient source detection



The Matched Filter

- Optimal detector for a *known* signal in *known* Gaussian noise
- Matches expected signal shape (template, *h*) to data (*s*), and sums

$$T(x) = (s \star h)[n] = \sum_{k=0}^{K} s[k]h[n-k],$$

- Pros: optimal for a given Gaussian dataset
- Cons: requires full signal knowledge, not "blind" to signal shape
- Performance: signal-to-noise ratios

Template matched to signal, *s*

$$d = \frac{\sqrt{\int_W s(t)^2 dt}}{\sigma}.$$

Template (*h*) and signal (*s*) mis-matched

$$d = \frac{\int_W s(t)h(t)dt}{\sigma\sqrt{\int_W h(t)^2 dt}},$$

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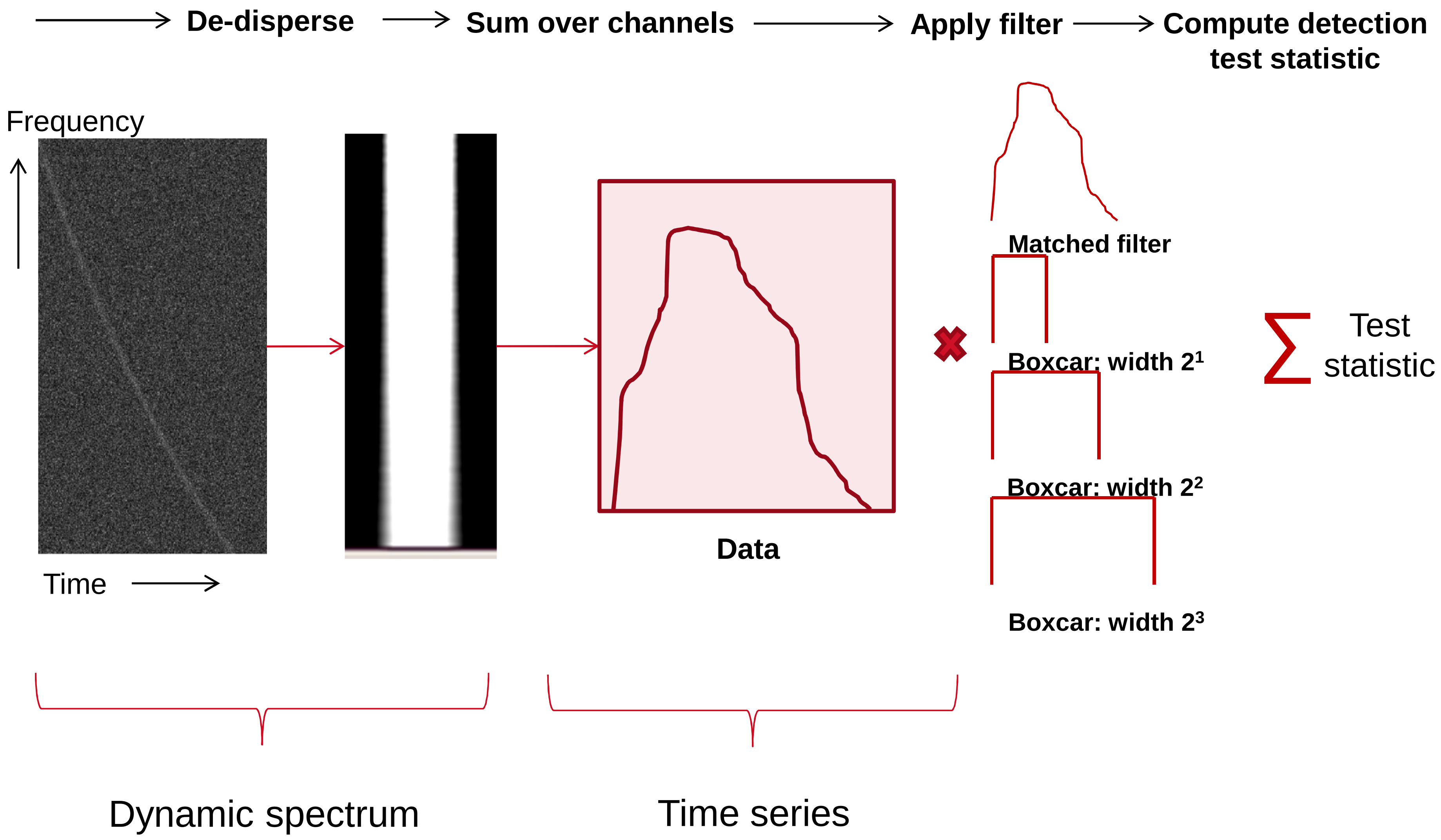
Time series MF implementation



Degrading factors

- Intrinsic
  - **Scatter broadening due to ISM multi-path**
- Extrinsic
  - Incorrect dispersion measure
  - Finite temporal/spectral sampling
  - Finite temporal window
  - **Mis-matched/approximate templates**

Degrading factors: ISM scattering

Characteristic scattering timescale:

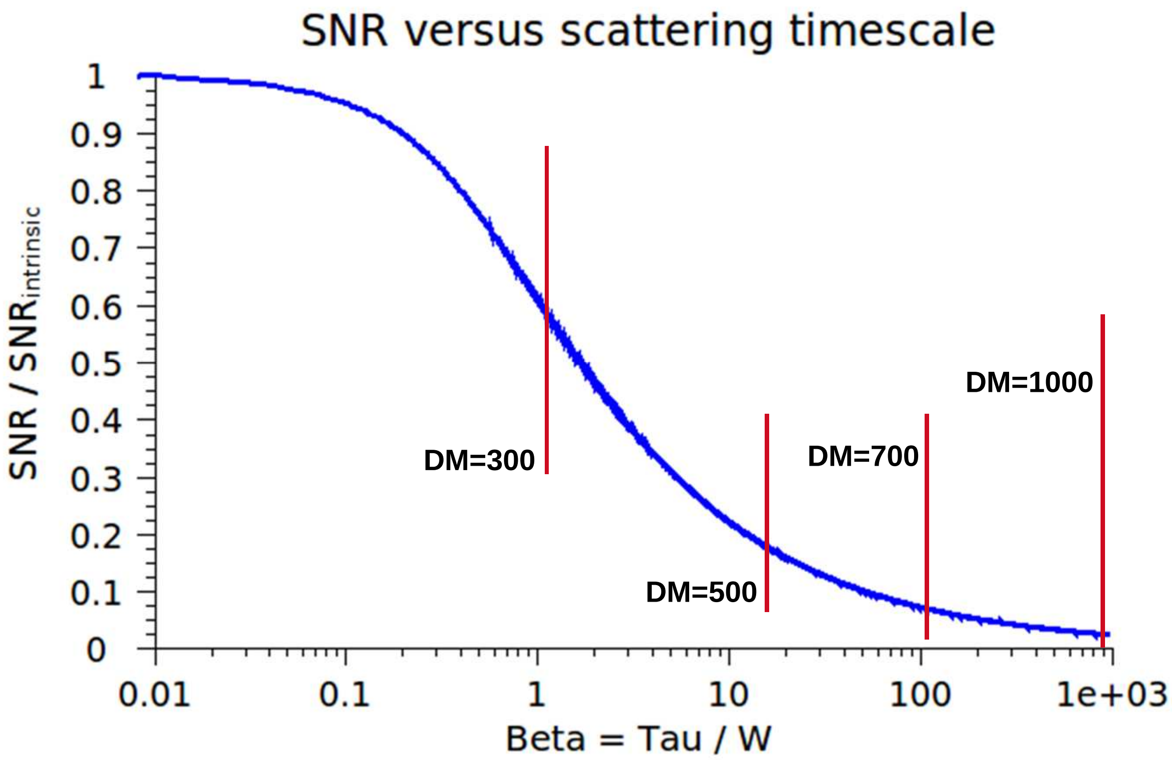
$$\log \tau_d = -3.72 + 0.411 \log \mathrm{DM} + 0.937 (\log \mathrm{DM})^2 - 4.4 \log \nu_{\mathrm{GHz}} \ \mu\mathrm{s}.$$

Cordes & Lazio (2002)

$$\frac{\mathrm{SNR}_{\mathrm{scat}}}{\mathrm{SNR}_{\mathrm{int}}} = \frac{\sqrt{W - \tau + \tau \exp(-W/\tau)}}{\sqrt{W}} = \sqrt{1 - \beta + \beta \exp(-1/\beta)}$$

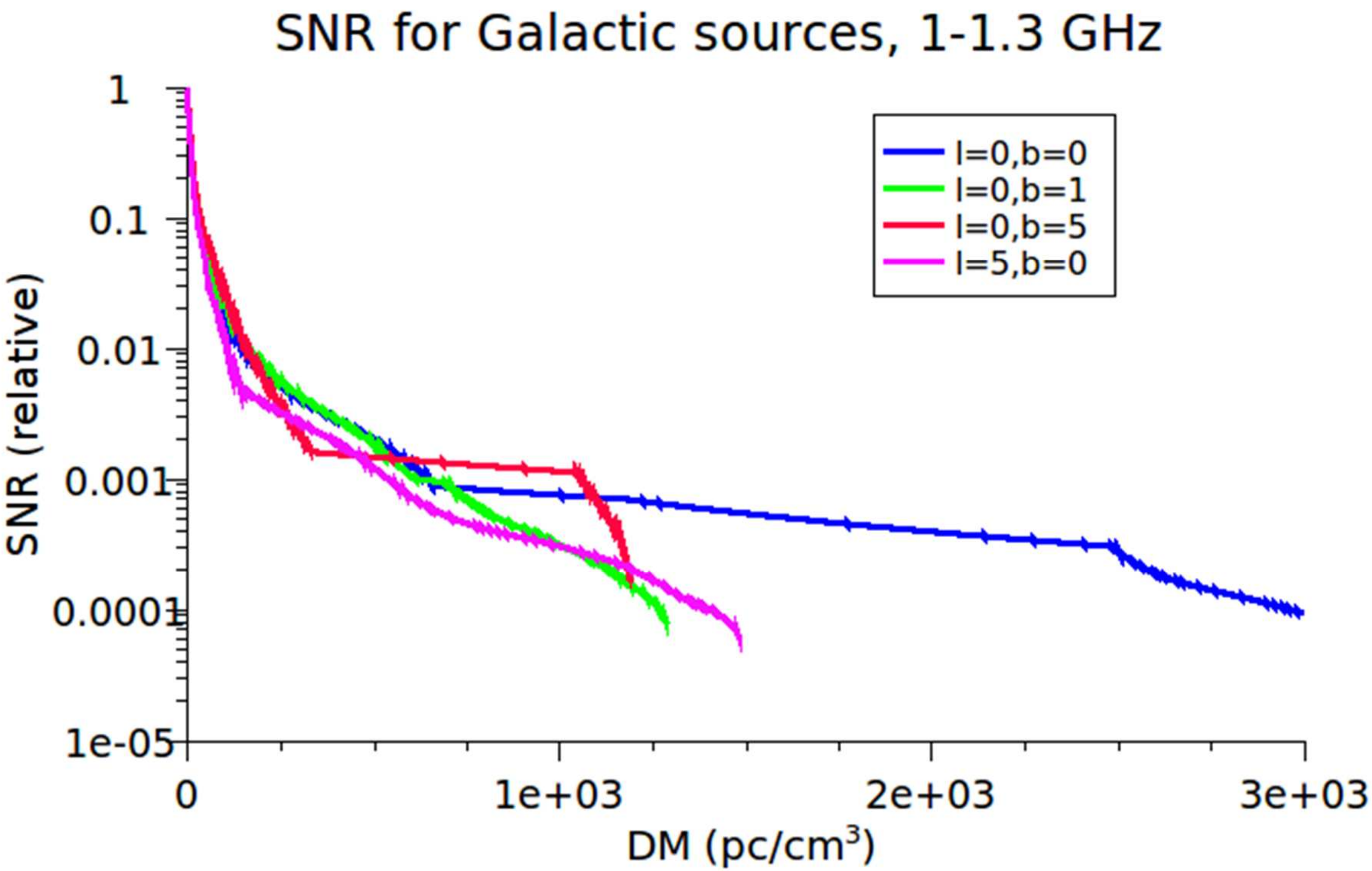
$$\beta = \tau / W$$

ASKAP parameters:
W = 1 ms
v = 1 GHz



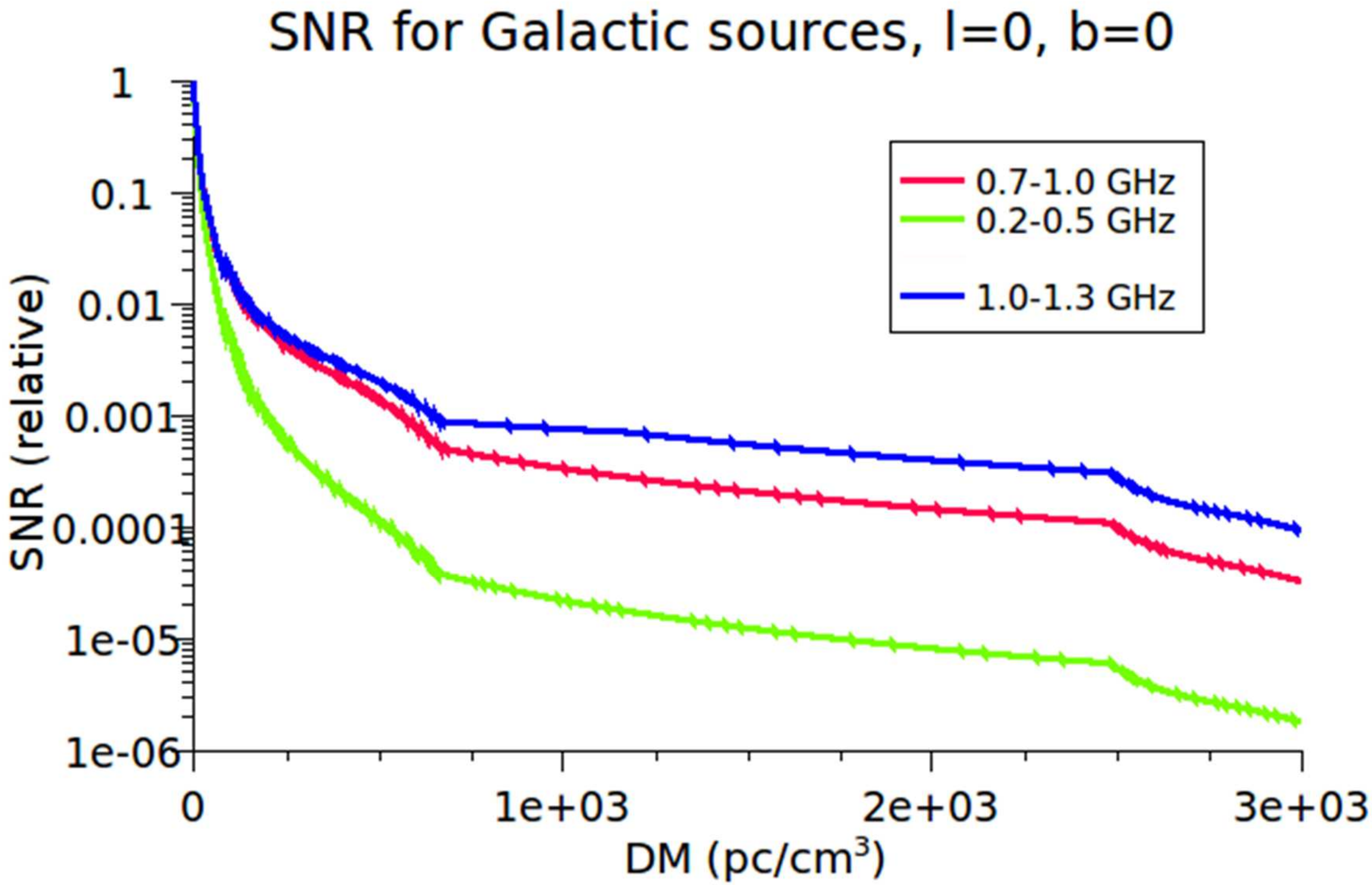
Impact of degrading factors: Galactic lines-of-sight

Relative detection performance for identical source at different DMs:



Impact of degrading factors: Frequency dependence

Relative detection performance for identical source at different DMs:



Hierarchy of signal knowledge

Dynamic spectrum power samples

Matched filter

Full signal knowledge required: temporal and spectral

$$\mathrm{SNR}_{\mathrm{DSMF}} = \frac{\sqrt{\sum_{W}\sum_{i=1}^{N_t} \bar{P}^2(t,\nu_i)\sqrt{\Delta t}}}{kT_{\mathrm{sys}}\sqrt{\Delta\nu}}.$$

Optimized boxcar templates

Partially blind: trial pulse widths, potentially trial spectral index

$$\mathrm{SNR_{CM}} = \frac{\mathrm{P_{dedisp}}}{\mathrm{P_{N_{dedisp}}}} = \sqrt{\frac{\Delta \mathrm{t}}{\mathrm{N}_{\mathbb{S}}\Delta\nu}}\frac{\sum_{\mathrm{s}\in\mathbb{S}}\bar{\mathrm{P}}(\mathrm{t_s},\nu_{\mathrm{s}})}{\mathrm{kT_{sys}}}.$$

Time series power (summed over spectral channels)

Matched filter

Full time domain signal knowledge required

$$\mathrm{SNR}_{\mathrm{MF}} = \frac{\sqrt{\sum_{W}\left(\sum_{i=1}^{N_t}\bar{P}(t,\nu_i)\right)^2\sqrt{\Delta t}}}{kT_{\mathrm{sys}}\sqrt{\Delta\nu}\sqrt{N_{\mathrm{ch}}}}.$$

Boxcar templates

Blind: coarse trial of pulse widths

$$\mathrm{SNR_{BMF}} = \sqrt{\frac{\Delta\mathrm{t}}{\mathrm{N_{ch}W}\Delta\nu}}\frac{\sum_{\mathrm{W}}\sum_{\mathrm{i}=1}^{\mathrm{N_t}}\bar{\mathrm{P}}(\mathrm{t},\nu_{\mathrm{i}})}{\mathrm{kT_{sys}}}.$$

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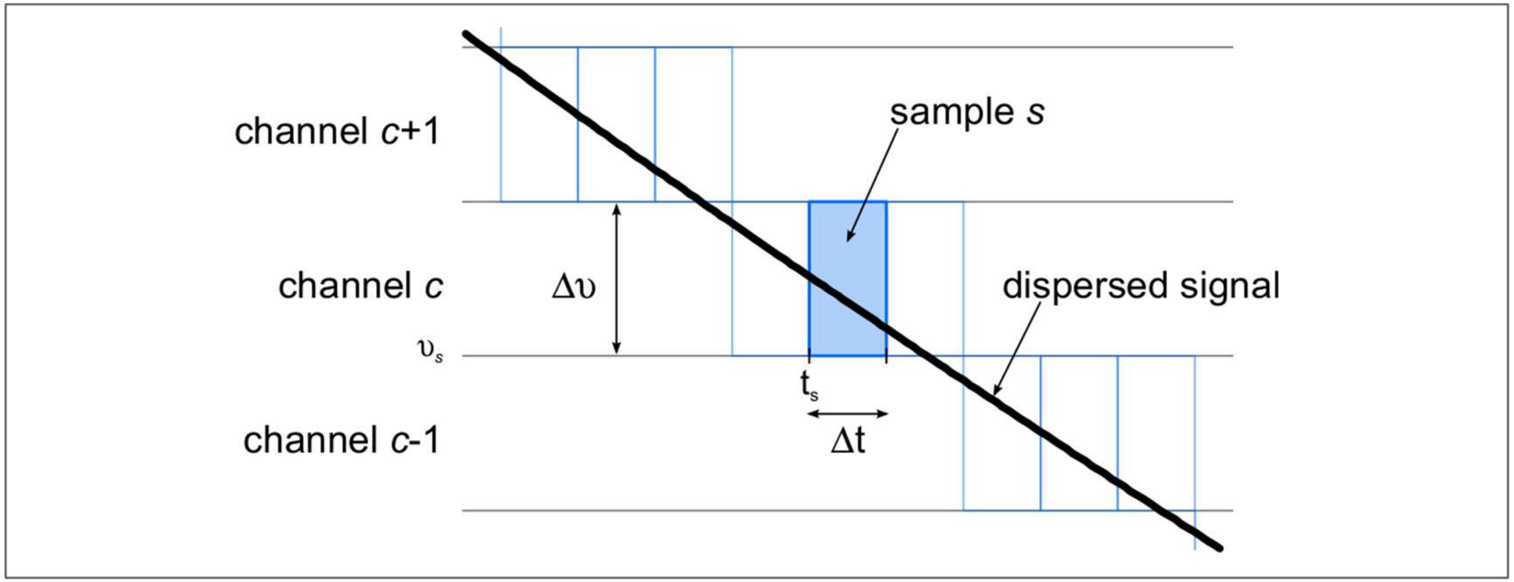
Dynamic spectrum detection

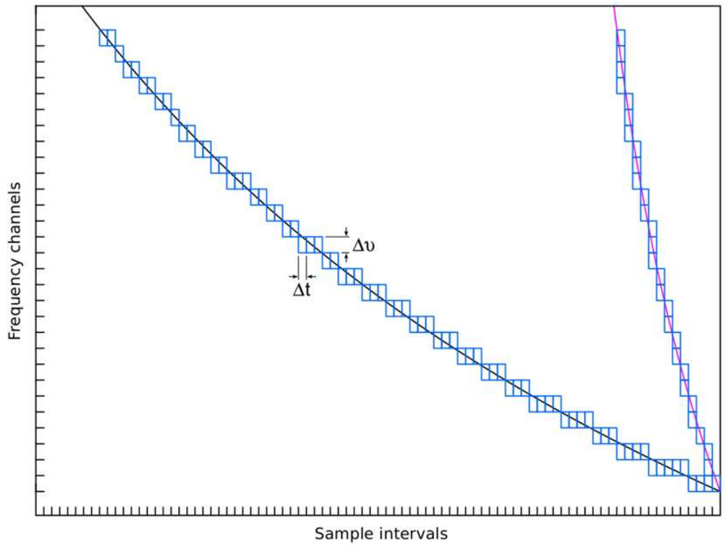
- Design of fast transient detector for CRAFT, using FPGAs to implement de-dispersion and detection algorithm
- Works directly with dynamic spectrum power samples from spectrometer

- Detector:
  - Choose samples according to expected power for a given DM: set spectral index (0), pulse width
  - Average power in a sample calculated analytically
  - Choose set of samples that maximises signal-to-noise ratio
  - "Sample-optimised" boxcar template

Clarke et al. (2011, in prep)

Dynamic spectrum detection



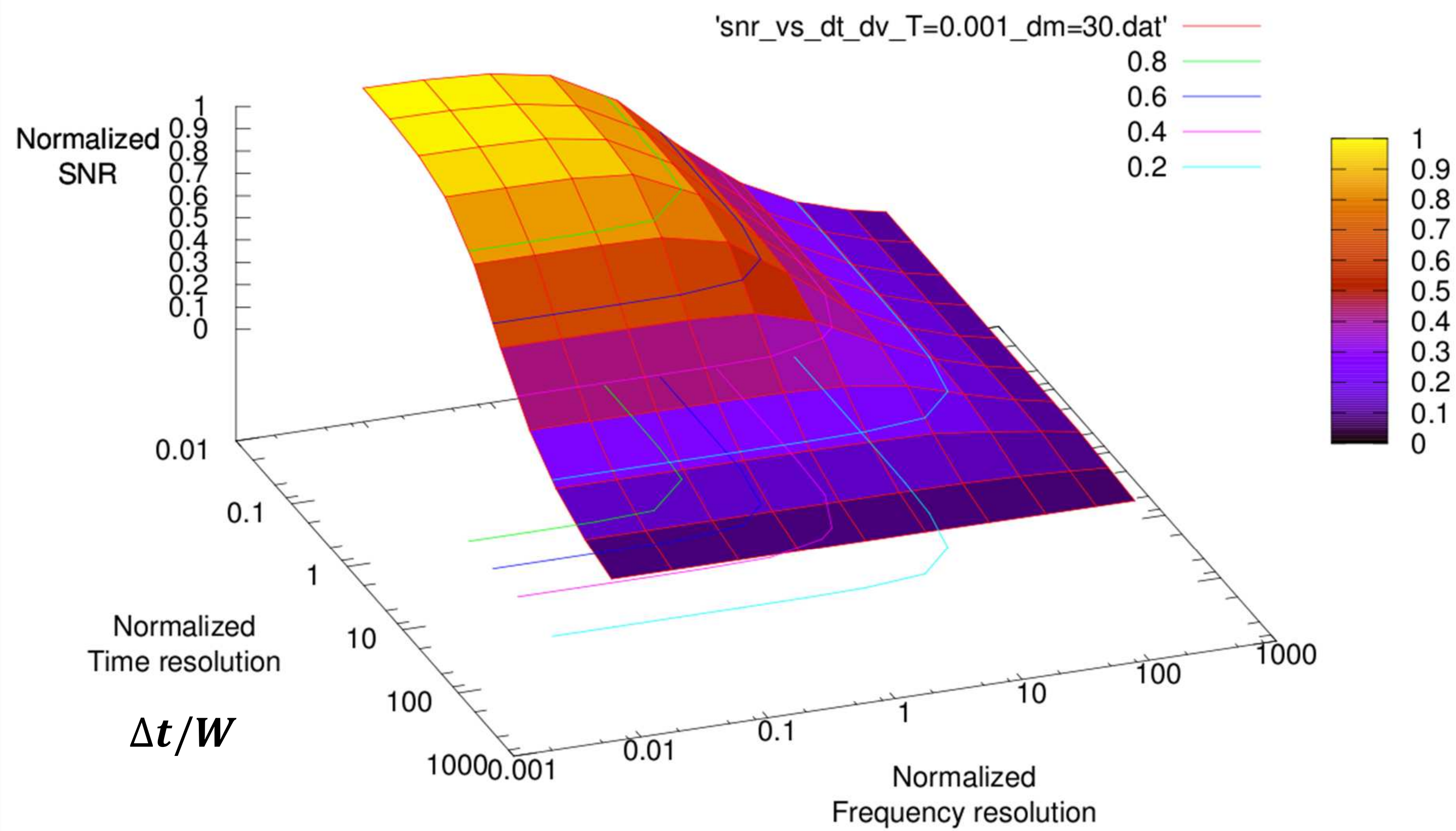


Inclusion criterion:

$$\bar{P}(t_\varsigma, \nu_\varsigma) > \left(\sqrt{\frac{N_{\mathbb{S}}+1}{N_{\mathbb{S}}}} - 1\right) \sum_{s\in\mathbb{S}, s\neq\varsigma} \bar{P}(t_s, \nu_s)$$

Clarke et al. (2011, in prep)

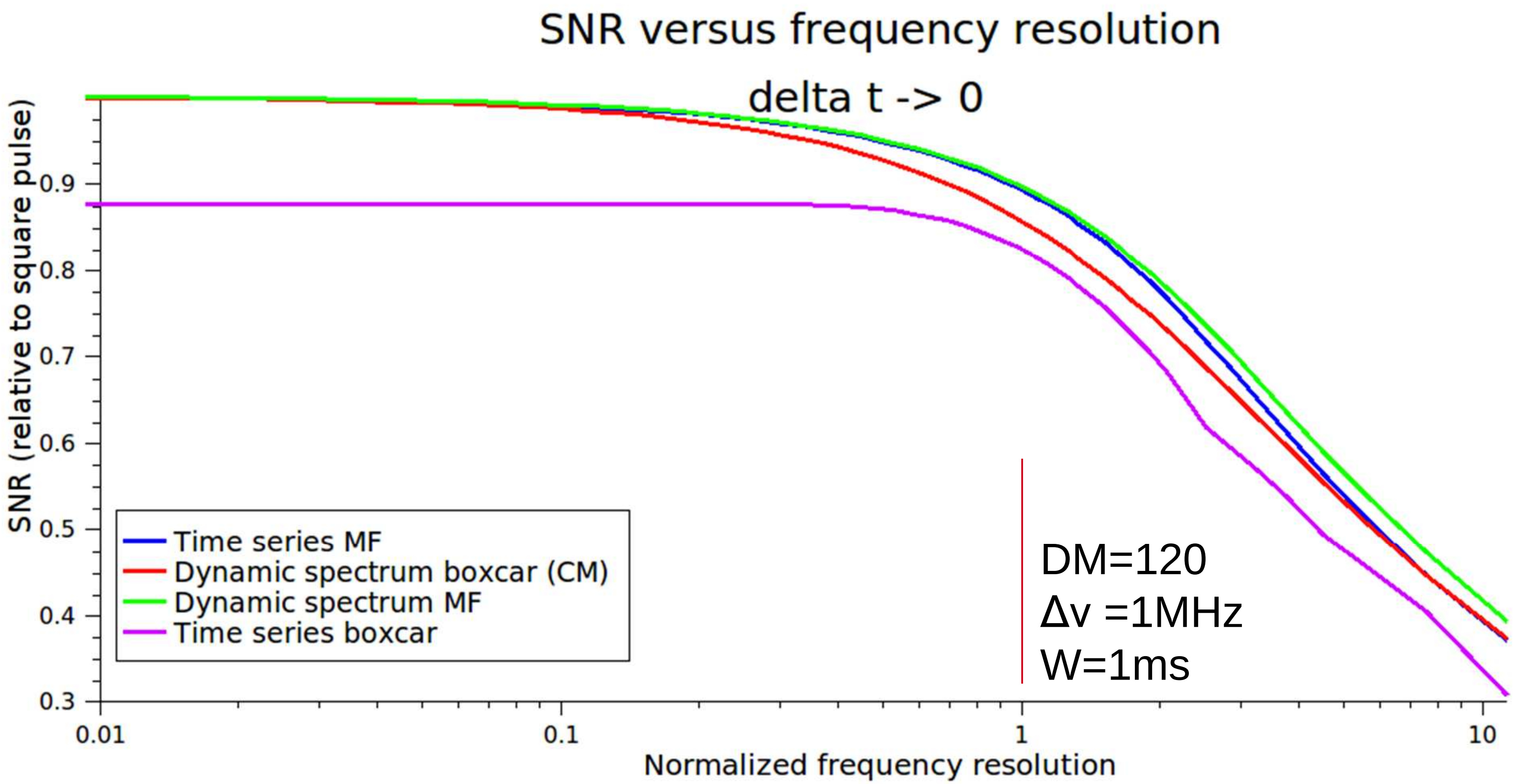
Asymptotic performance



$\Delta t / W$

$8.3 \times 10^{-3} DM \Delta\nu / (\nu^3 W)$

Performance comparison



ASKAP parameters:
v = [1.0,1.3] GHz
Δv_{TOT} = 300 MHz

$$8.3 \times 10^{-3} DM \Delta\nu / (\nu^3 W)$$

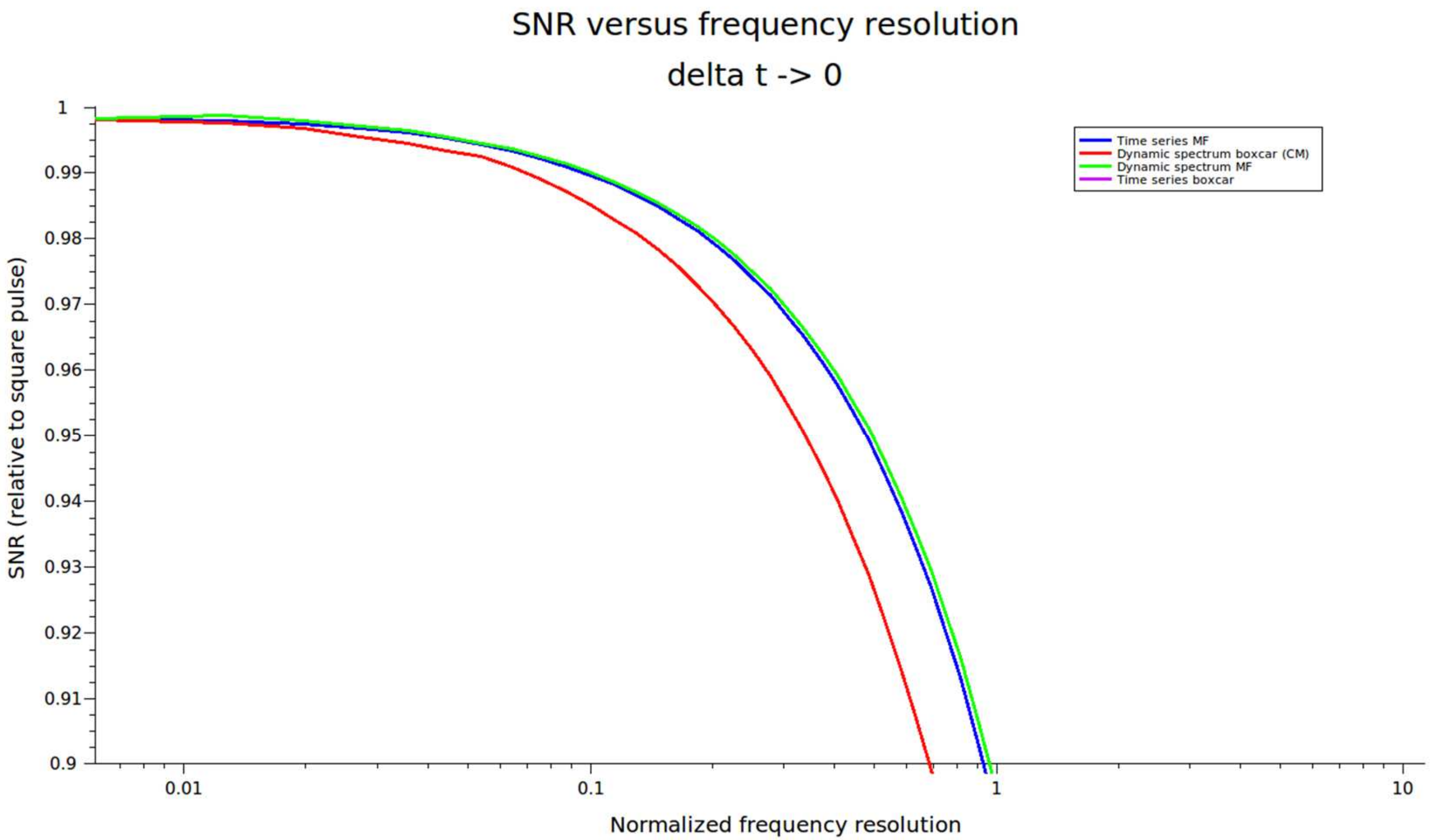
Summary

- High DM detections difficult, particularly at low frequencies
- Optimal matched filter rarely achievable ⟶ smart boxcar template applied to dynamic spectrum dataset can recover some lost performance
- Working directly with dynamic spectrum samples retains signal power, while minimising noise power ⟶ boxcar template can achieve improved performance

Next steps:

- Balance combination of DM steps / spectral index steps / pulse width steps for optimal detection with a given FPGA design and architecture
- Compare performance with other FT experiments (e.g., VFASTR)

Performance comparison



Performance comparison