Using 2DFFT method to search Fast Radio Bursts

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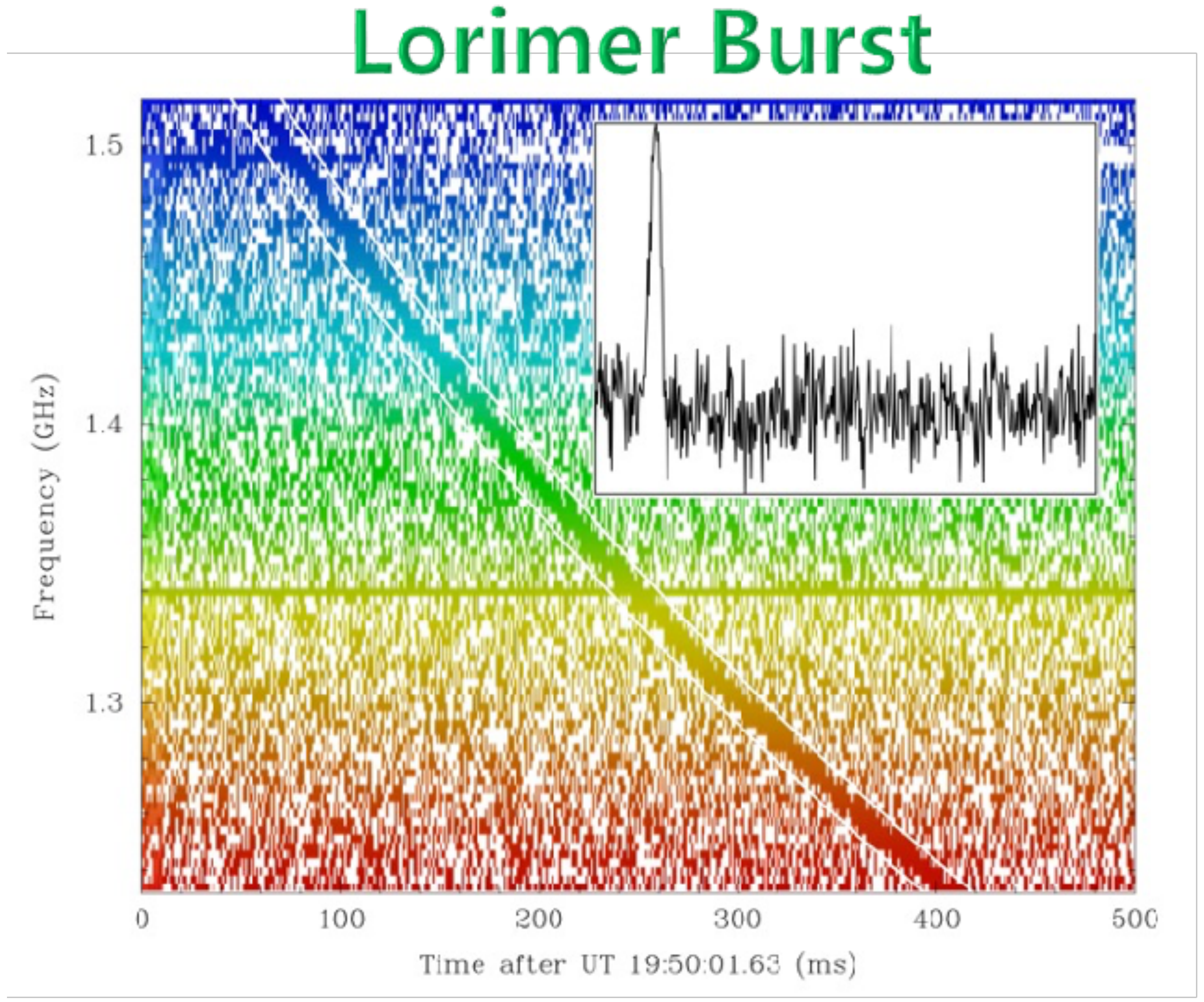
2023 July 19th
Shenyang

Lorimer Burst



(Lorimer et al. 2007)

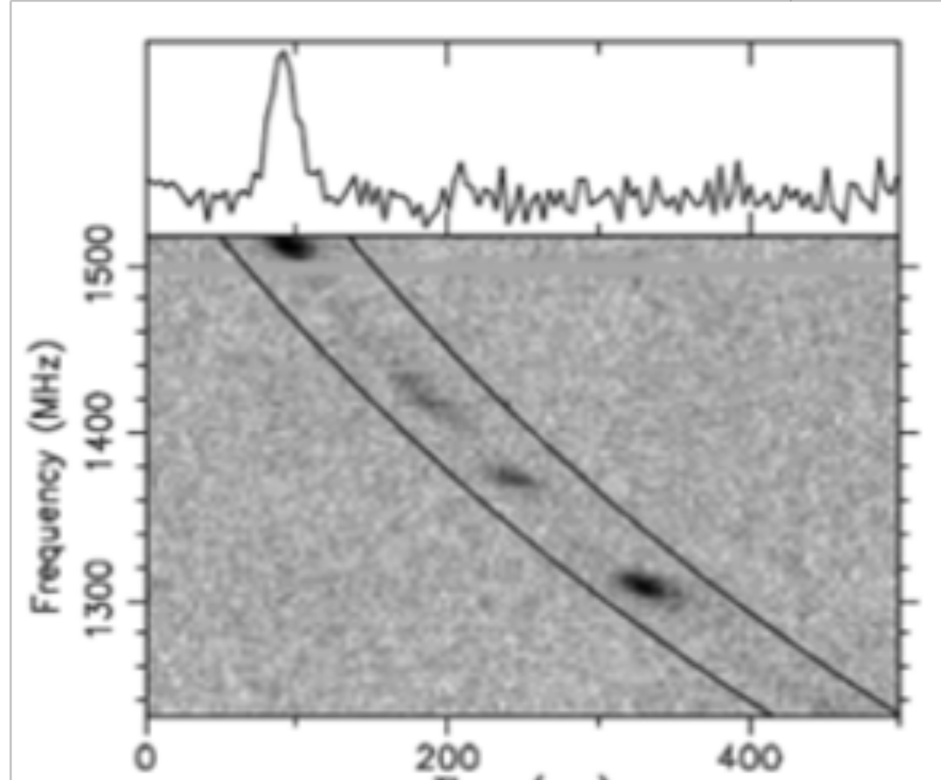
High DM Pulsar ?

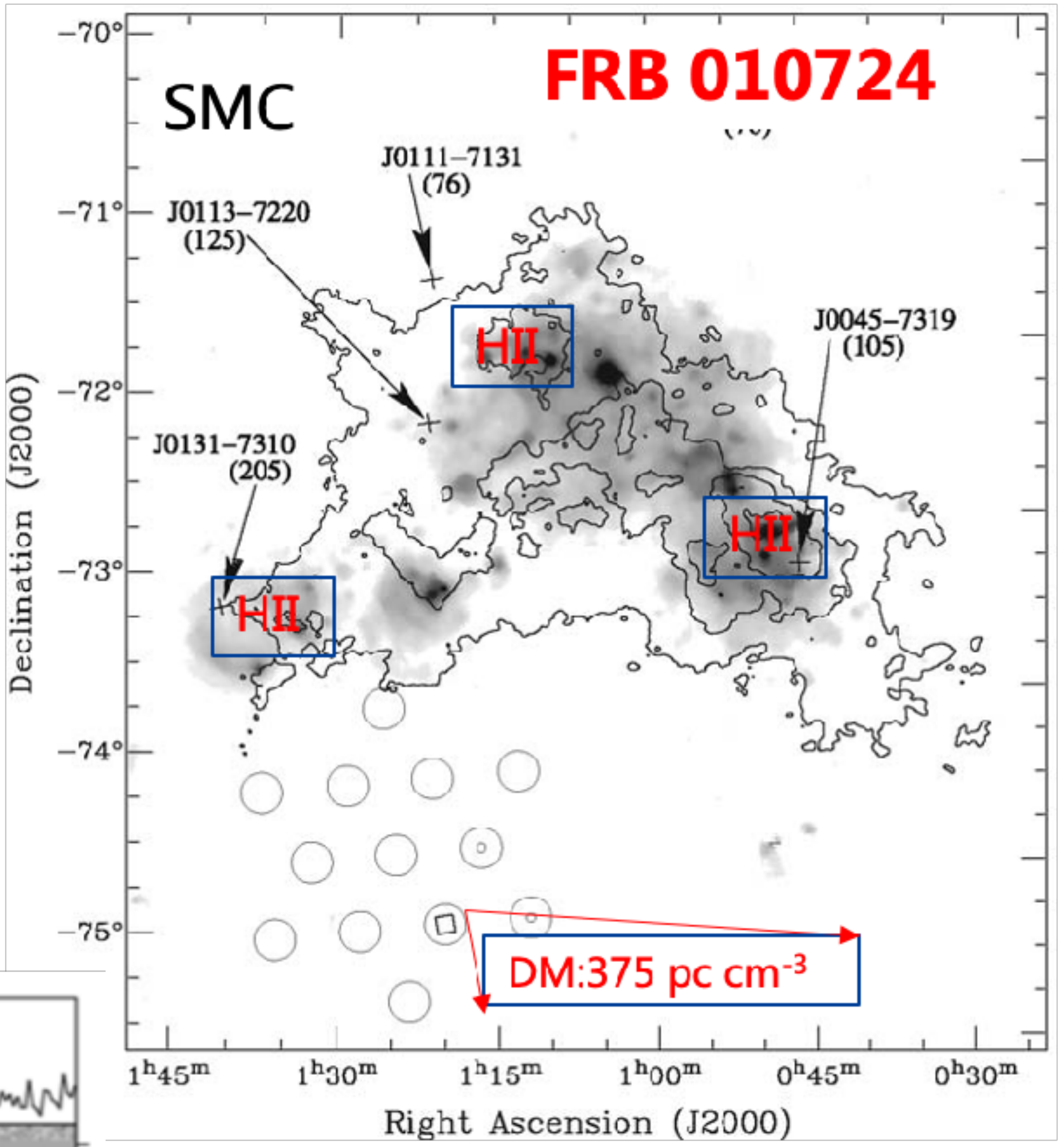
No follow-up detection:

- 50 hours 2001
- 40 hours 2007
- Trail DM : 0-500 pc cm-3
- High Galactic latitude

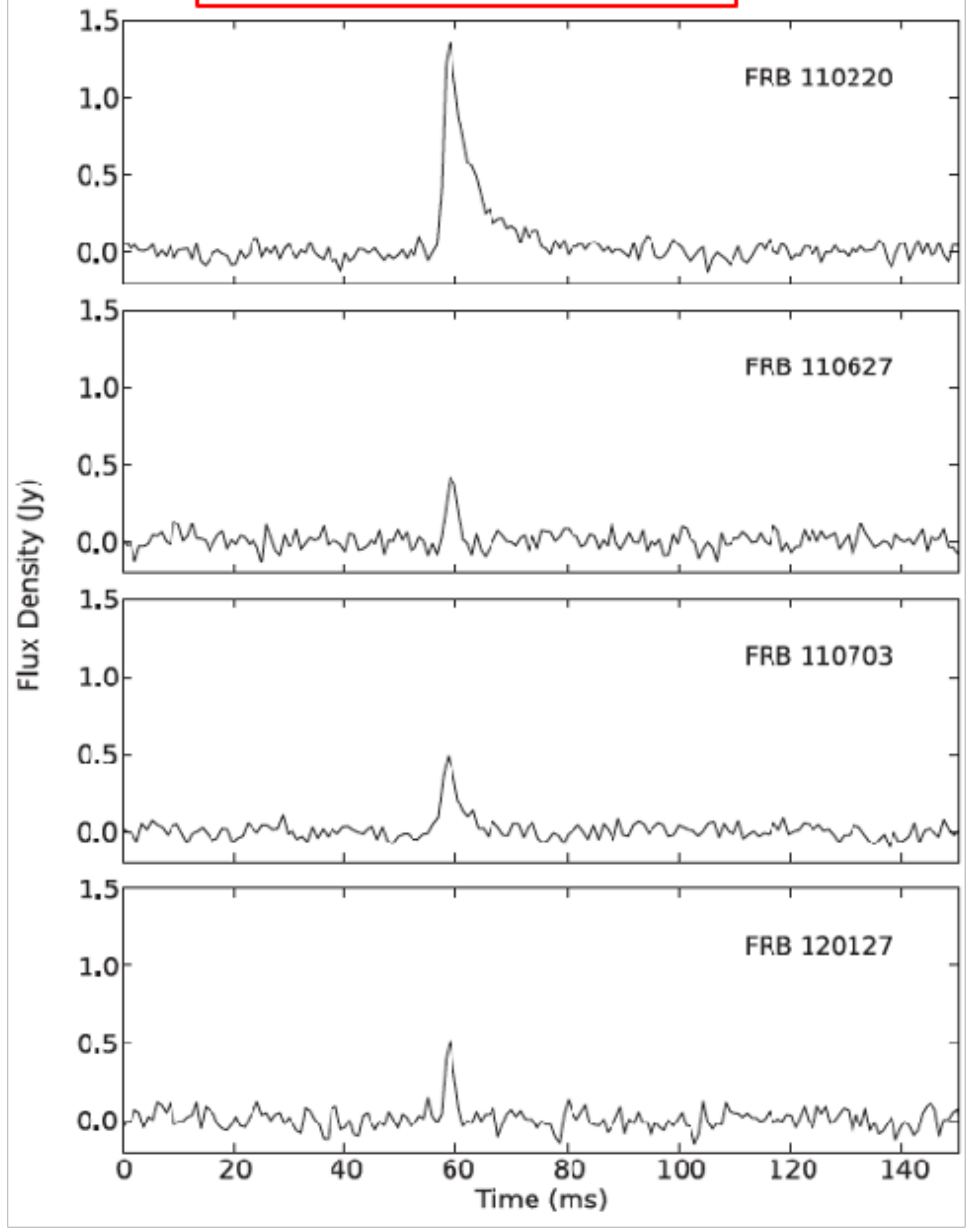
Peryton?

- Only show in 1/13 beam





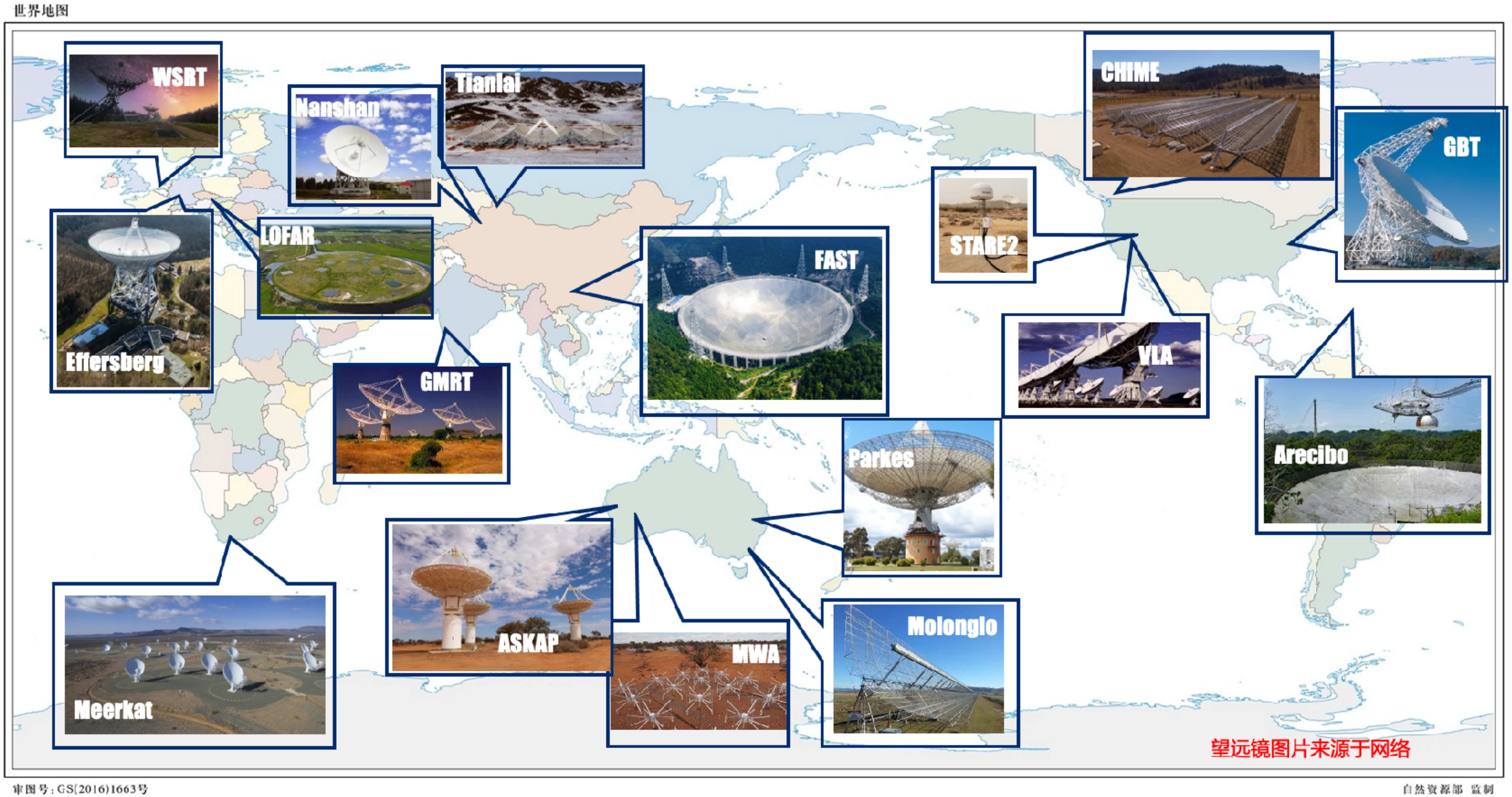
(D. Thornton et al. 2013)



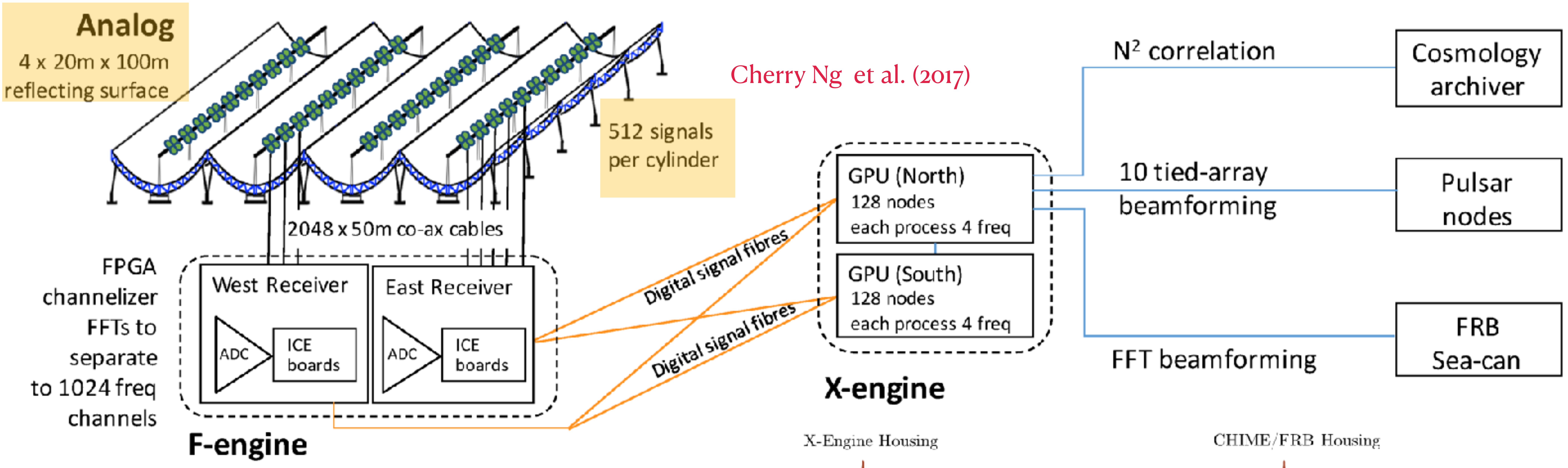
$DM_{MK} < 6\% \ DM_{Obs}$

- High DM
- High Galactic latitude
- Duration: ~ms

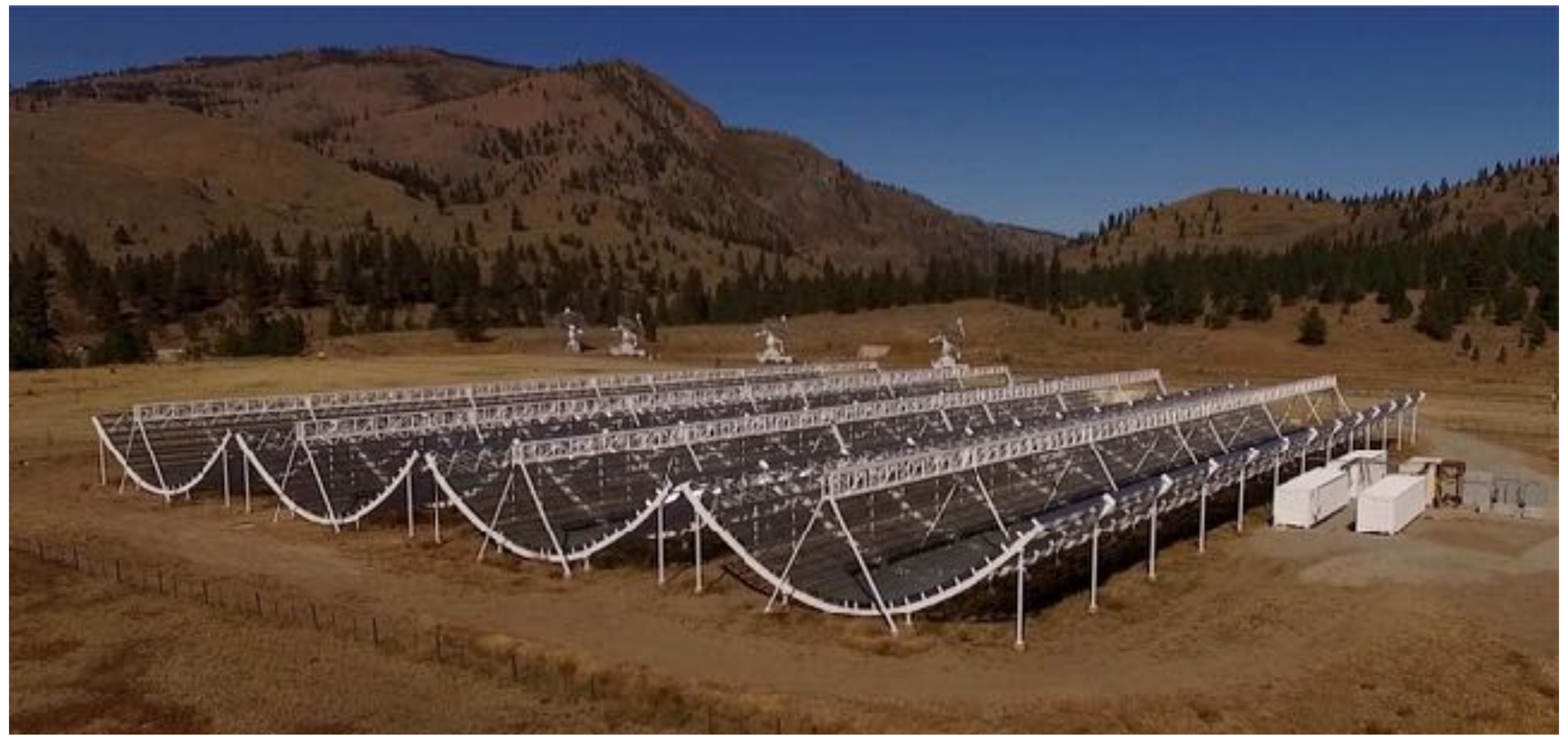
The FRB Surveys

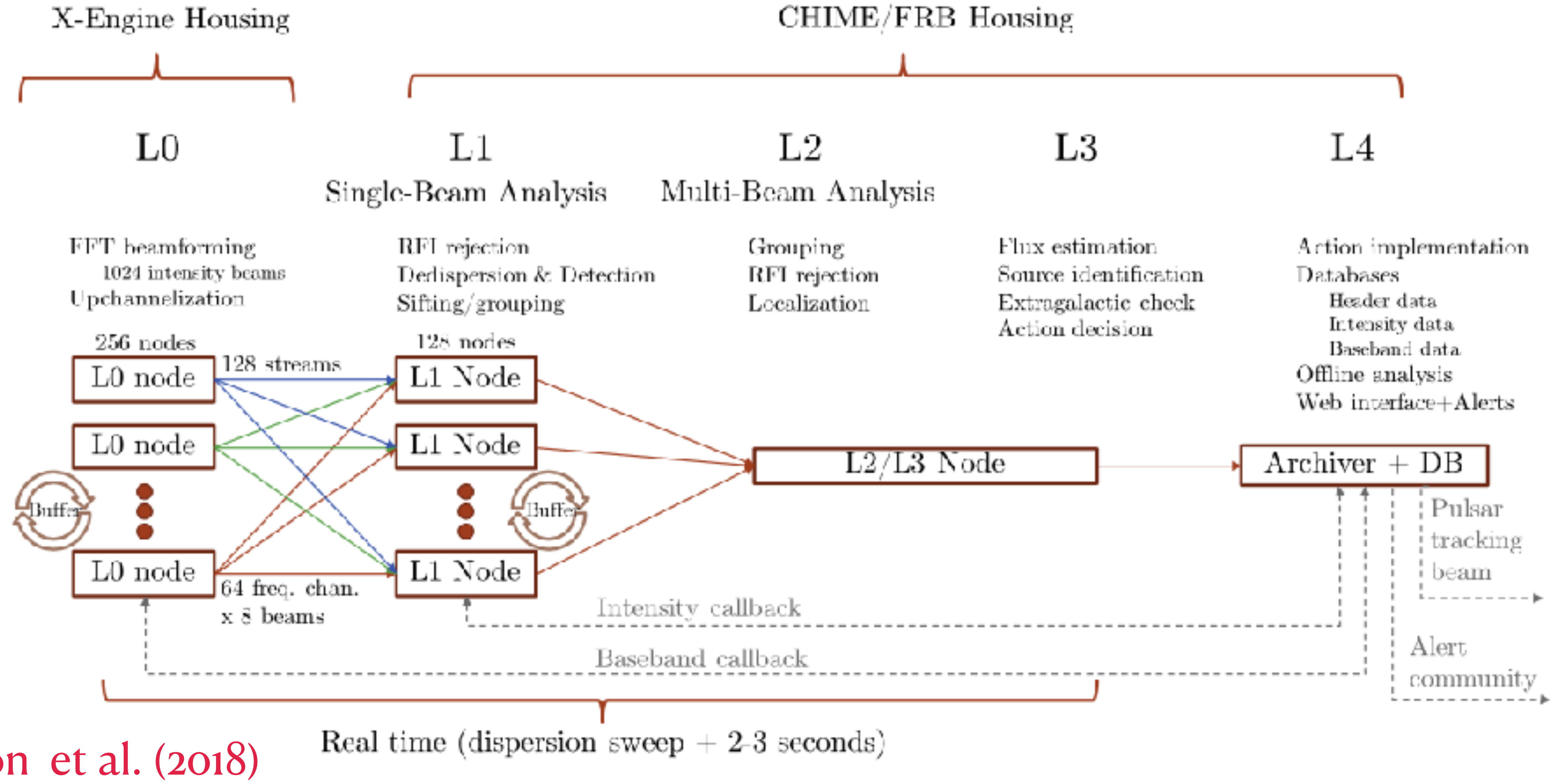


CHIME



Cherry Ng et al. (2017)





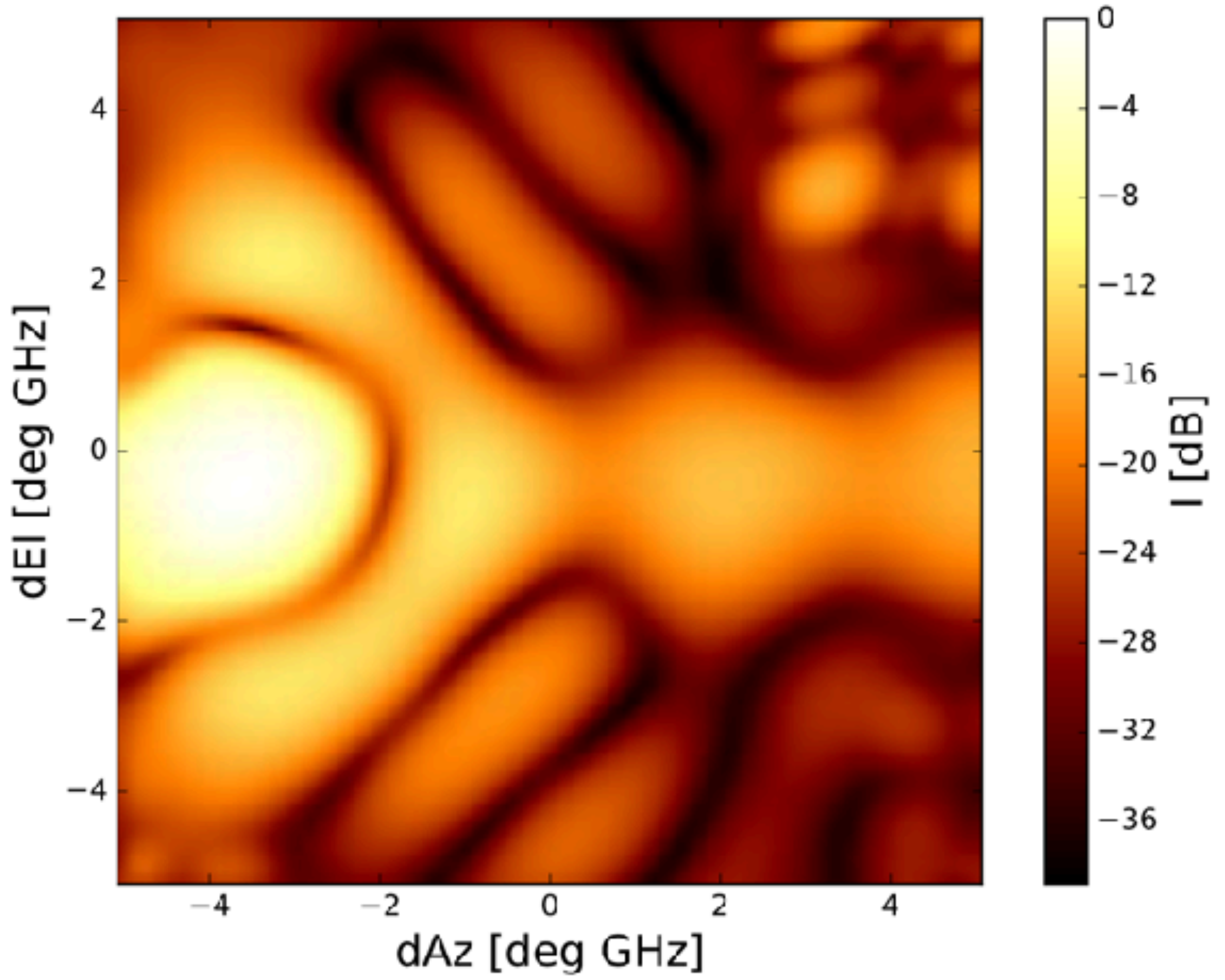
CHIME Collaboration et al. (2018)

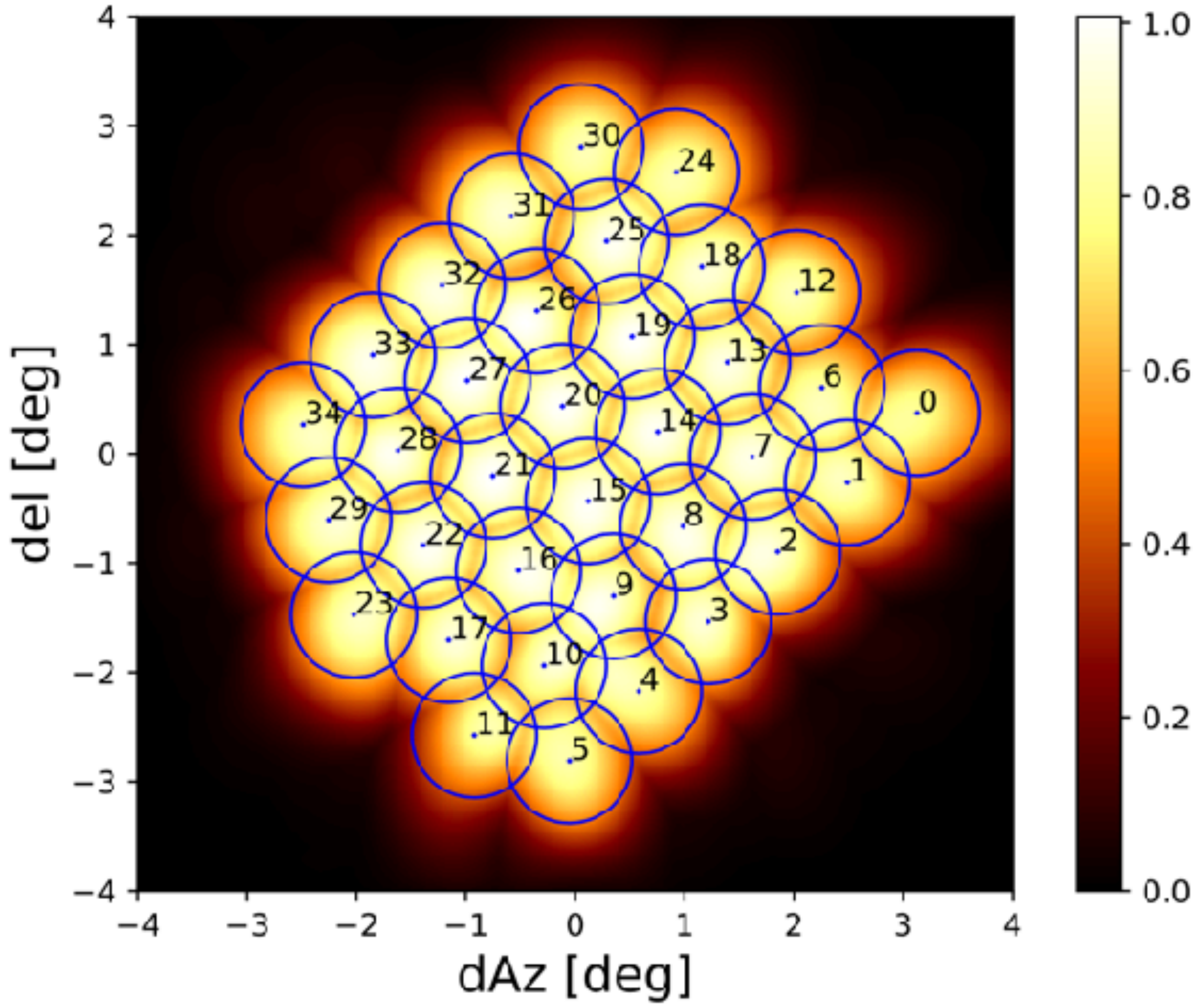
ASKAP

C. W. James, et al,2019

Phase Array Feed

Dimeter :12 m
Beam: ~1 deg
PAF: ~5.5 deg





Phase Array Feed

Fly's eye mode

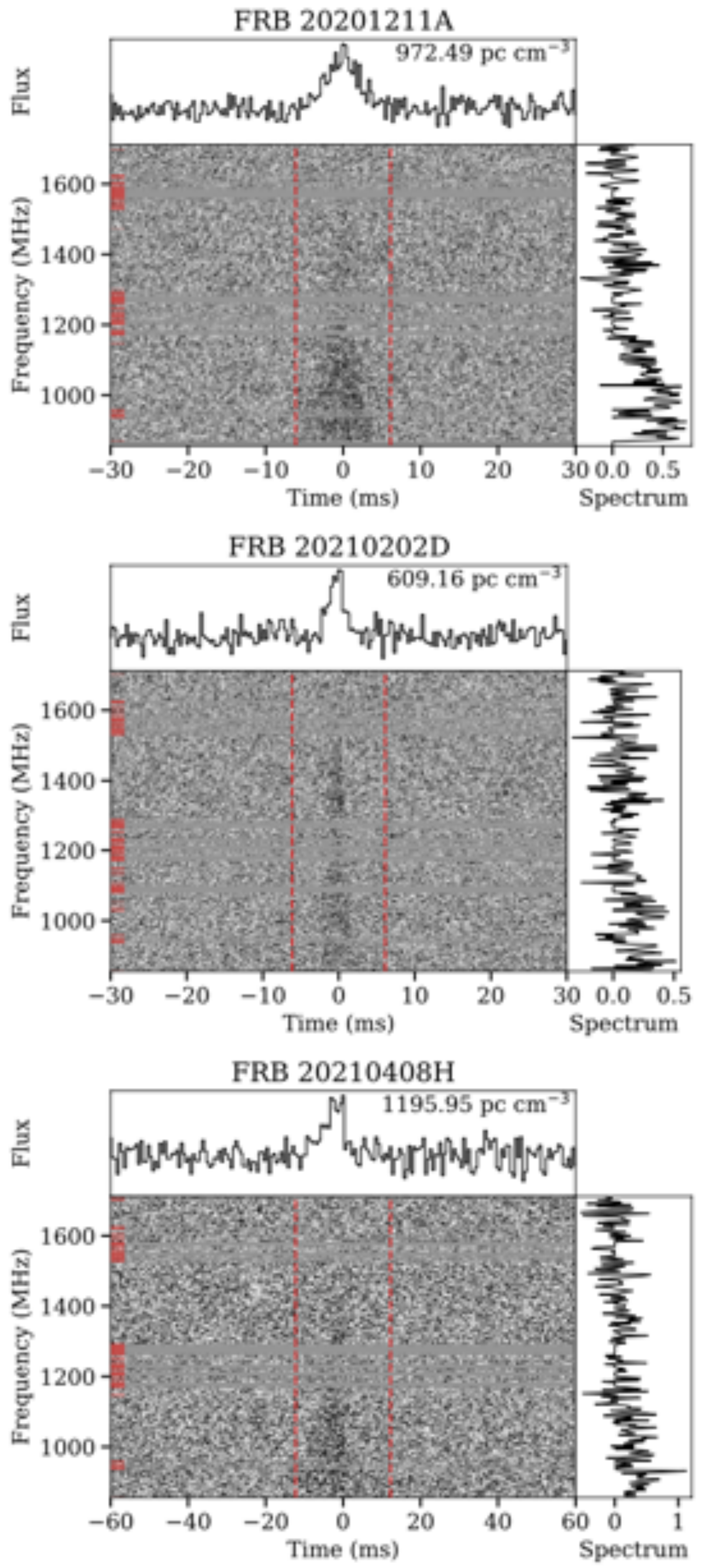
- Use 36 beams in each path
- Use 36 antennas pointing independently
- Effectively 36 x 36 = beams
- Powerful tool for finding fast transients

MeerKat

- 64 13.5-m telescopes
- Central compact array
- South Africa
- Along with the HERA, ASKAP and the MWA, precursors to the final SKA.

Specifications

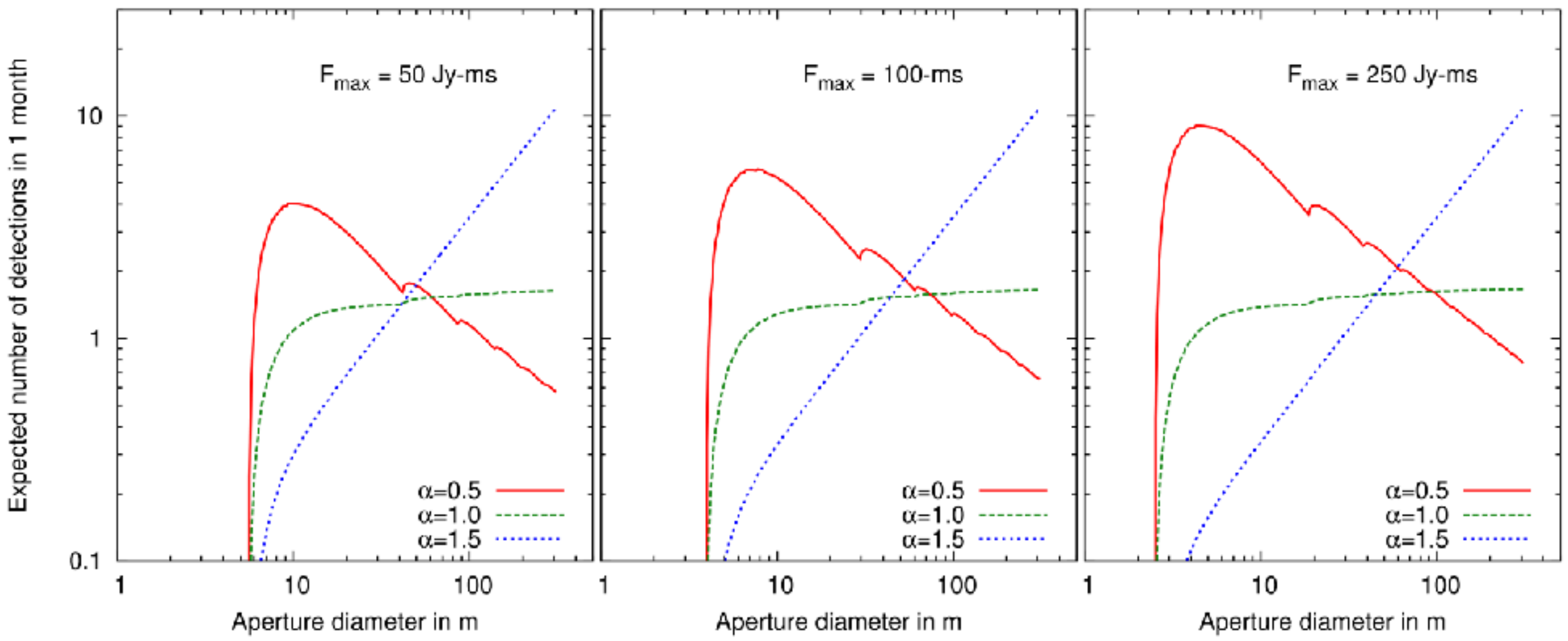
Number of antennae	64
Dish diameter	13.5 m
Minimum baseline	29 m
Maximum baseline	8 km
Frequency bands (receivers)	0.58 – 1.015 GHz 0.9 - 1.67 GHz 8 – 14.5 GHz
Continuum imaging dynamic range at 1.4 GHz	60 dB
Line-to-line dynamic range at 1.4 GHz	40 dB
Mosaicing imaging dynamic range at 1.4 GHz	27 dB
Linear polarisation cross coupling across –3 dB beam	–30 dB



The system overview is on going....

Deep Synoptic Array

Vedantham et al. (2016) Condition: T_{sys}=60 K, η=60%, $\Delta\nu$ = 500 MHz, ν_c=1.5 GHz, $N_{stations} = 10$



The relatively shallow slope of the FRB logN–logF curve implies that a modest telescope array with N~10 and d<6m aperture is sufficient to detect and localize a large population (>1 month⁻¹) of FRBs.

- 110 × 4.65-m dishes
- Owens Valley Radio Observatories
- continuously survey for FRBs at 1280 – 1530 MHz
- Localization < 3”
- 100 FRBs per year

Parameter	Value
Number of dishes *	110
Dish diameter	4.65 m
Aperture efficiency	0.65
System temperature ‡	25 K
Frequency band	1280 – 1530 MHz
Number of channels	8192
FRB search sensitivity (7.5σ, 1 ms) †	< 1.7 Jy ms
Field of view	10 deg^2
Maximum baseline	2.6 km
FRB localization accuracy	± 1.5 arcsec
Survey speed	3.1×10^4 deg^2 m^4 K^{-2}

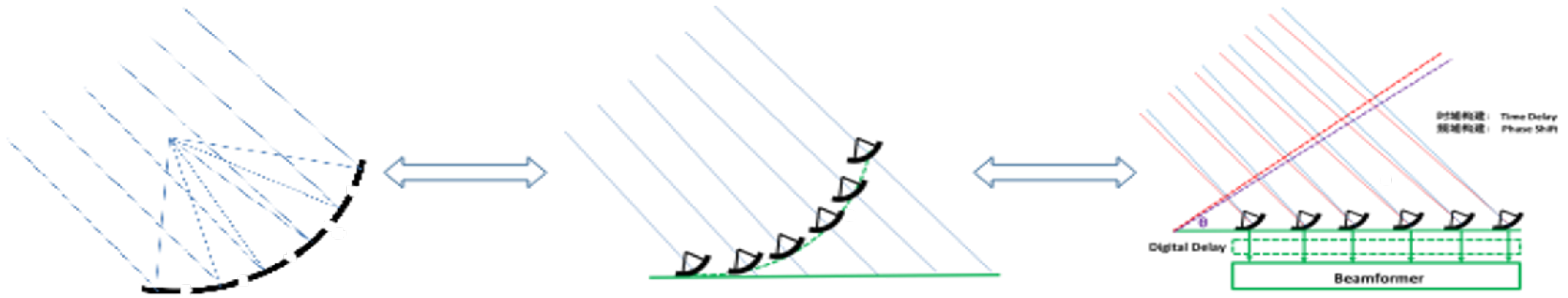
Small Dishes Interferometry

Advantage:

- Portable
- Matured technique
- Extensible deployment
- Low Coast

Disadvantage:

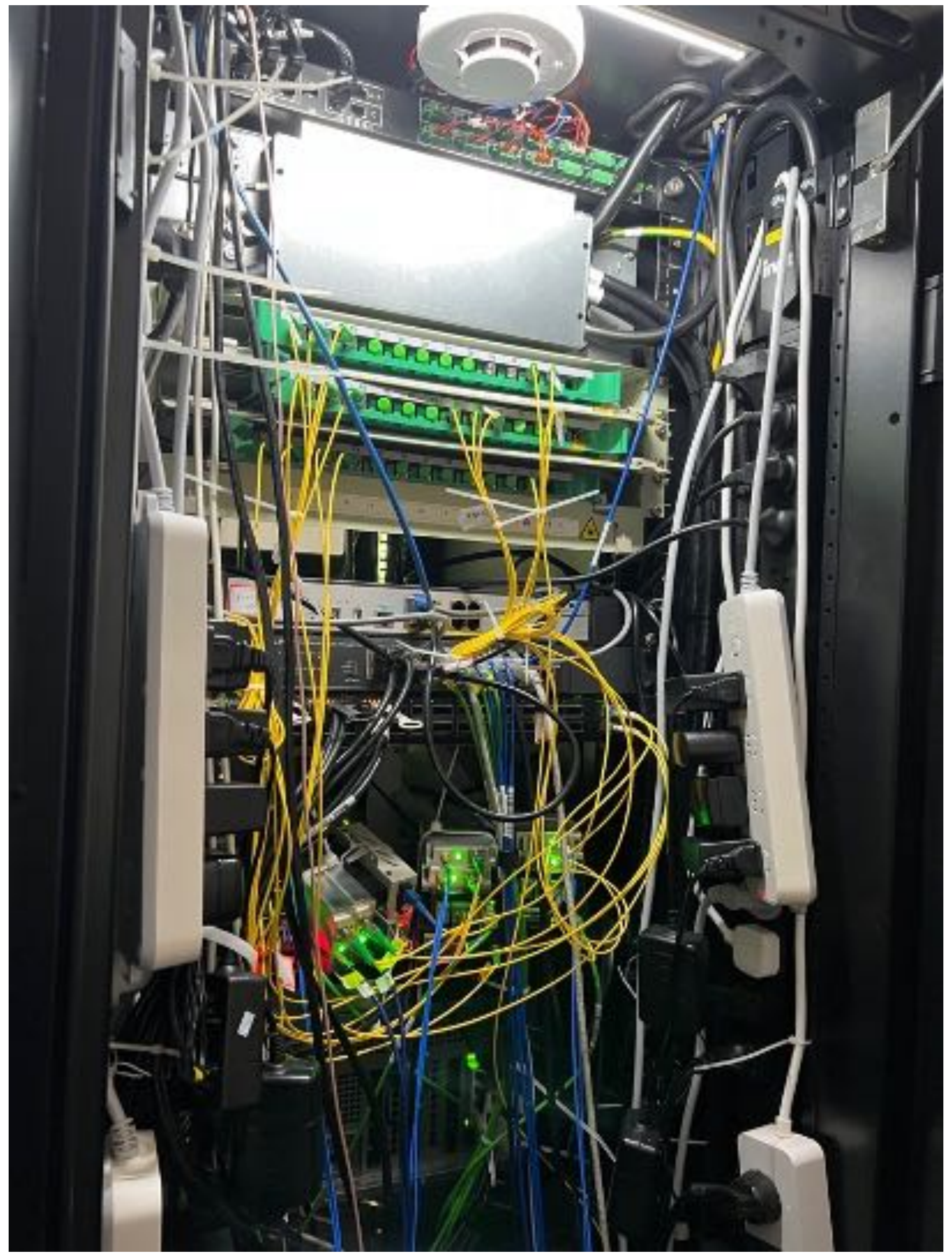
- High computing cost
- Complex algorithm
- High Data rate

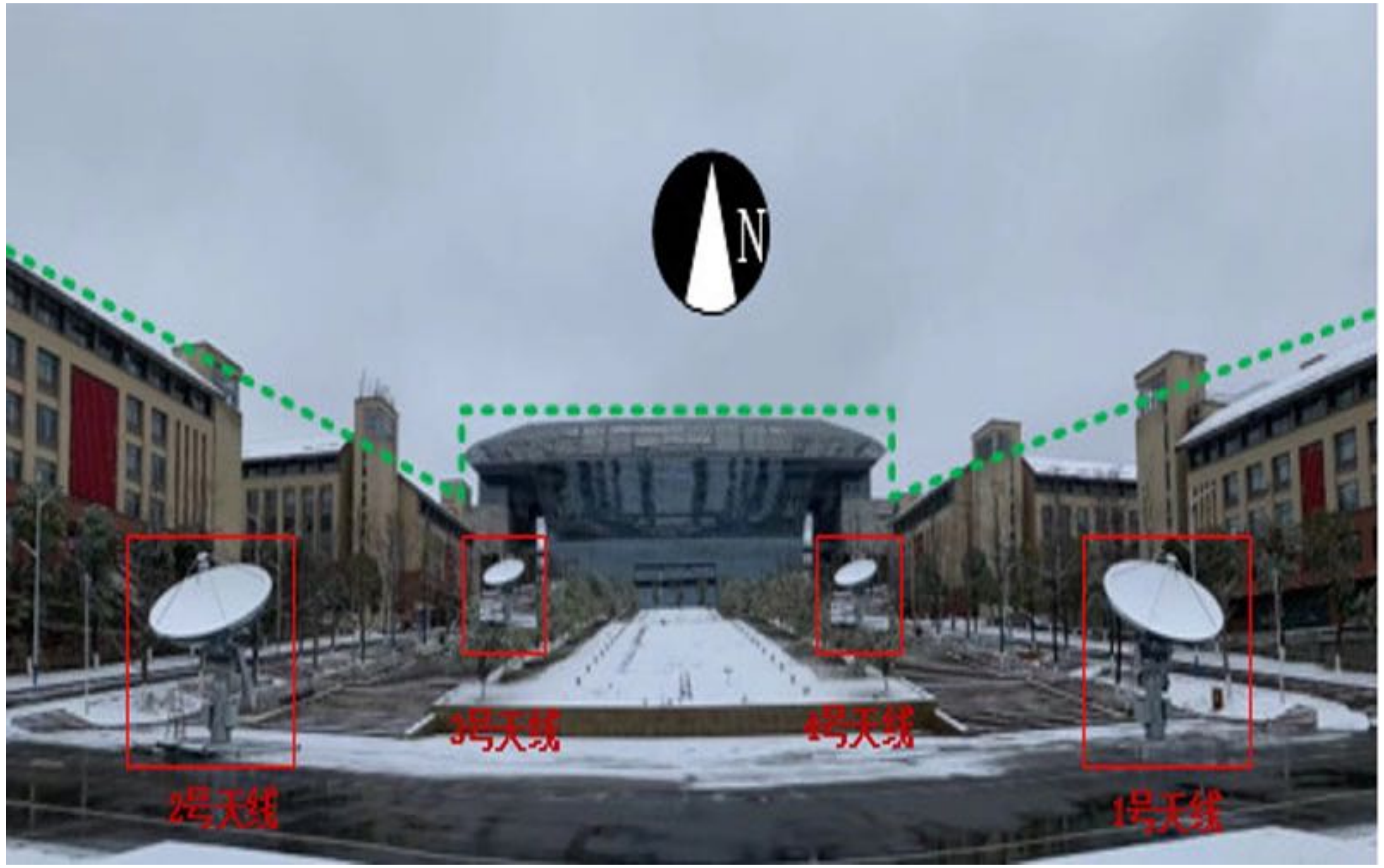


Small Dishes Array in China

Gui Zhou Normal University
(Ru-shuang Zhao)

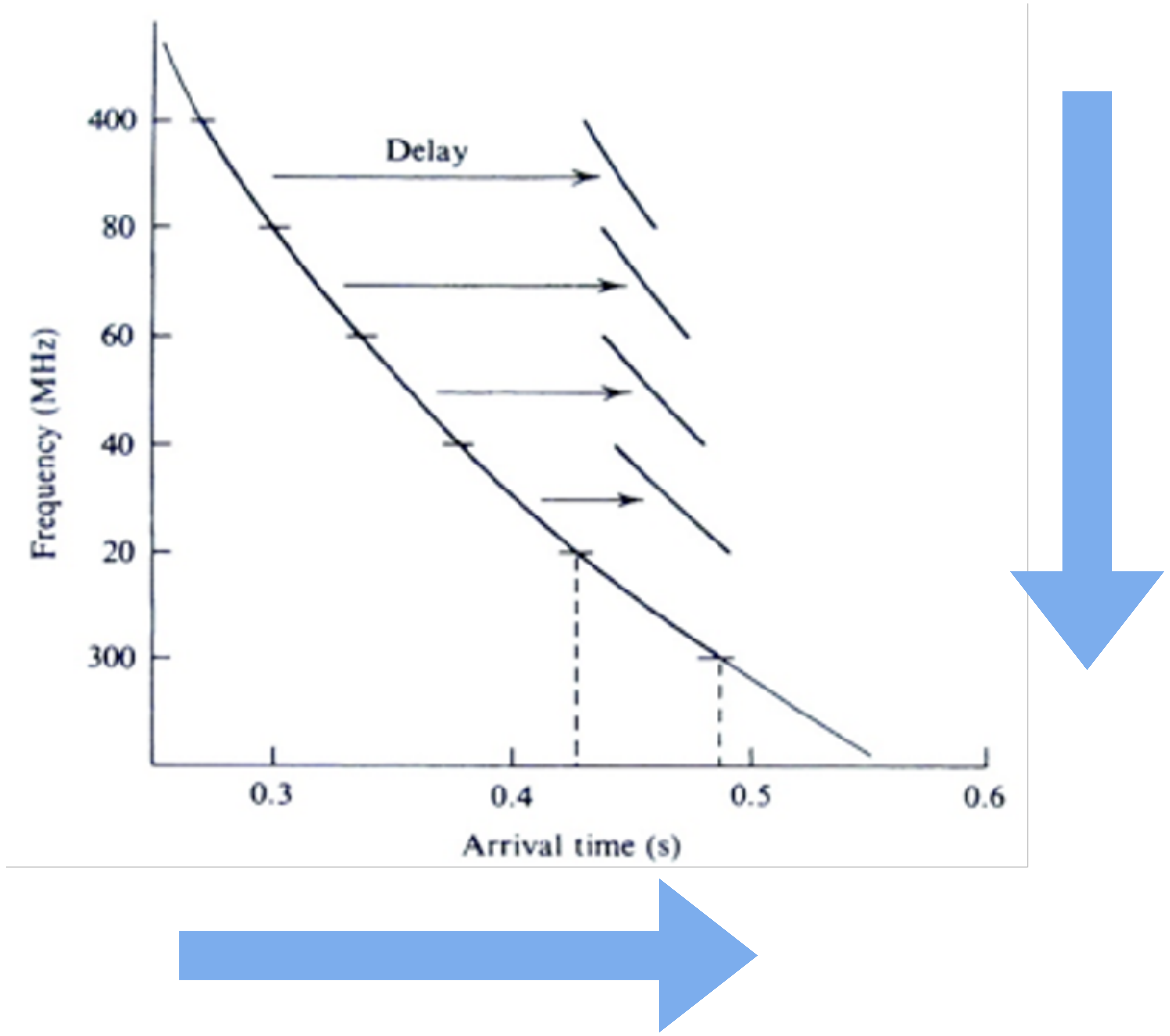
- 4 × 4.5 m dishes
- L-band (1-1.5 GHz)
- Cost: 200,000 Yuan per dish

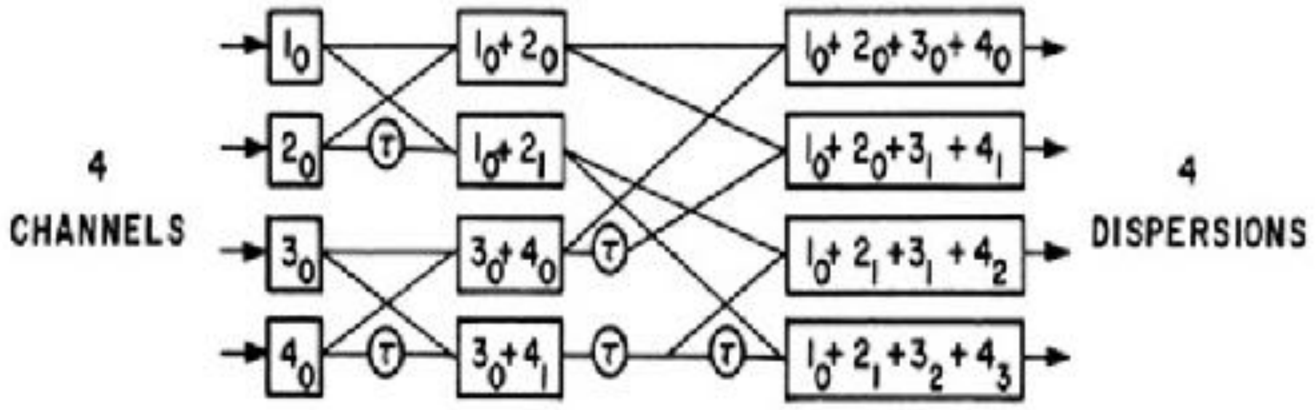




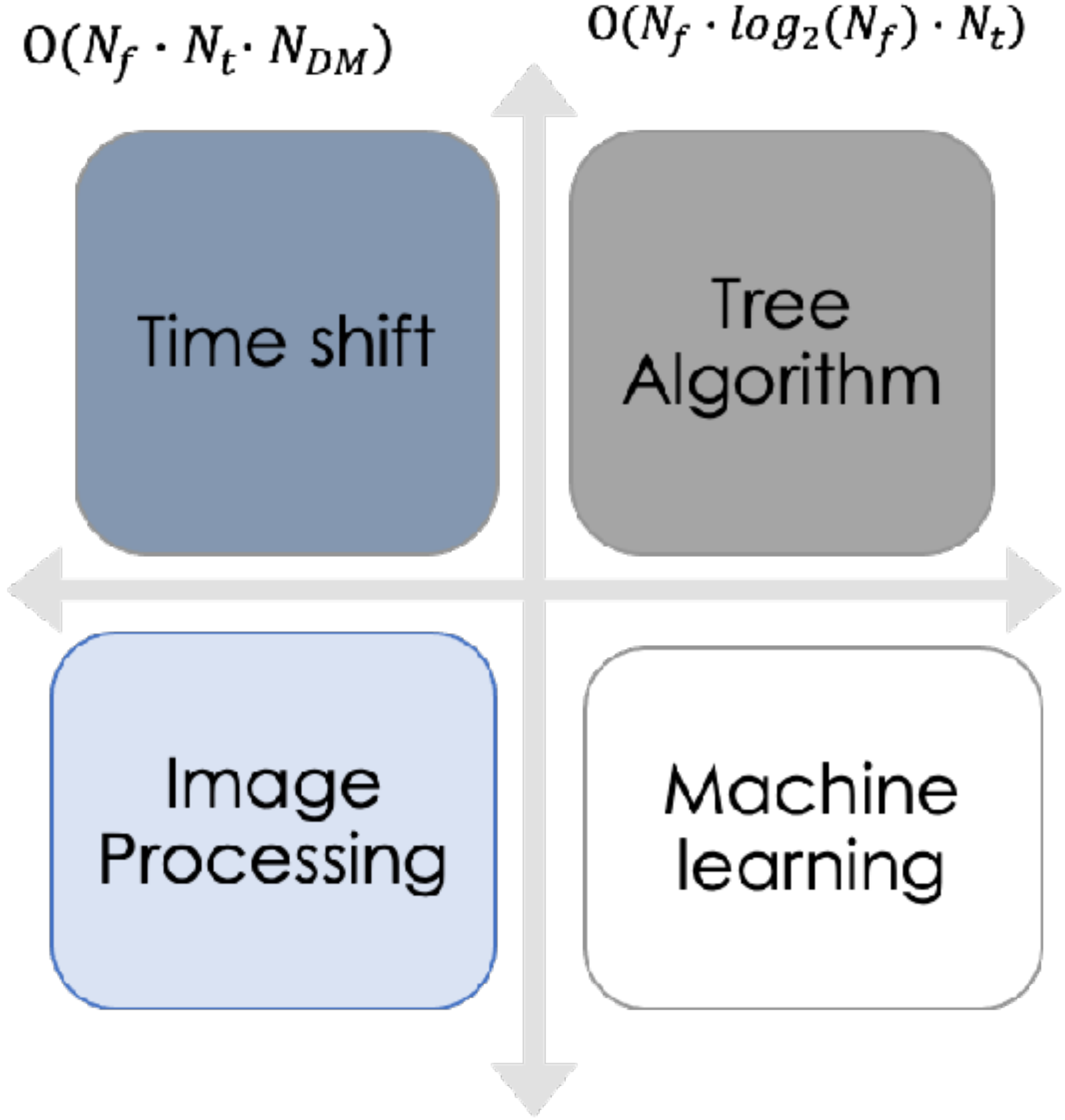
How to search FRBs

De-dispersion



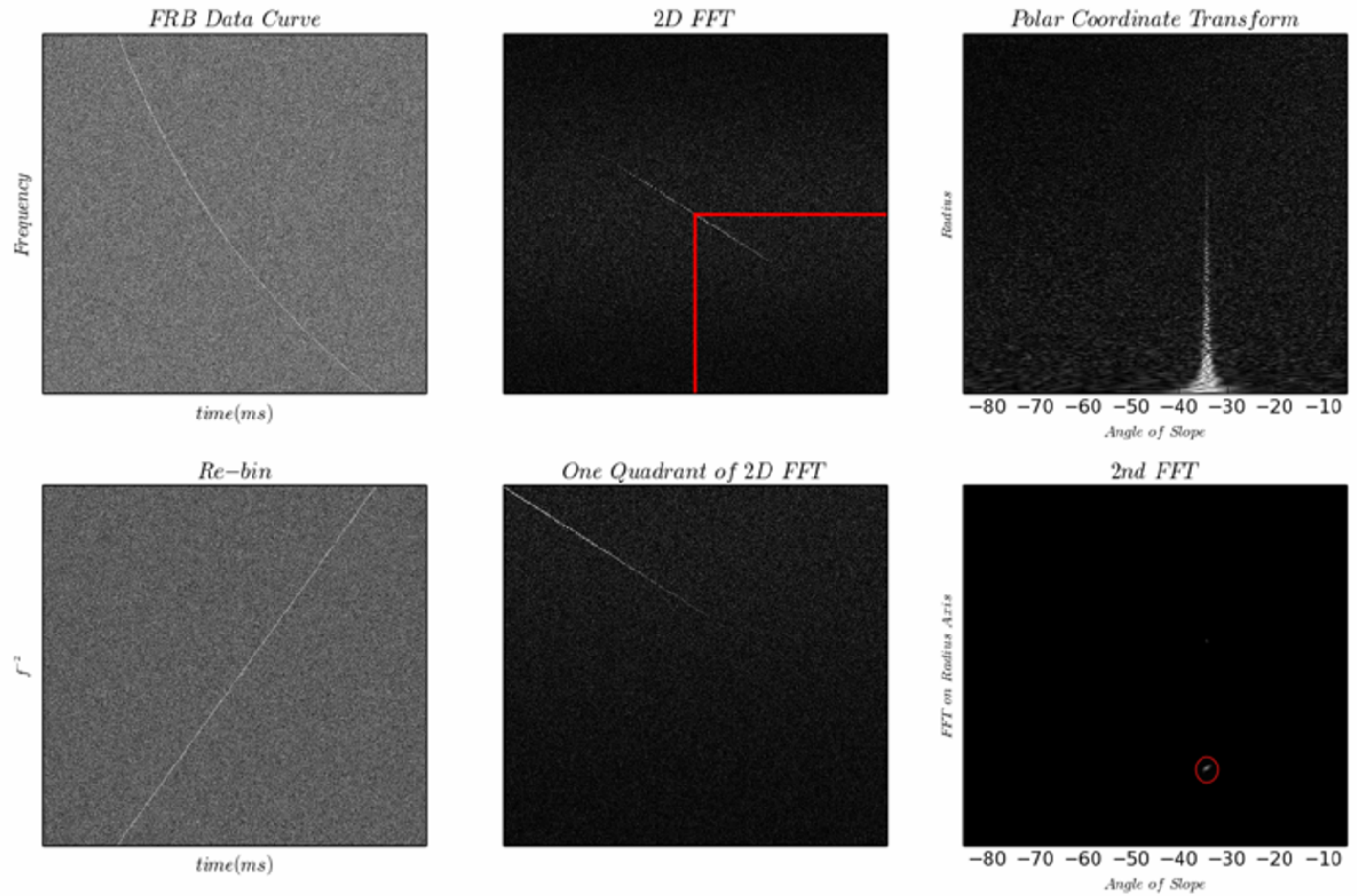


(Taylor, J. H. 1974, A&AS, 15, 367)



2DFFT method

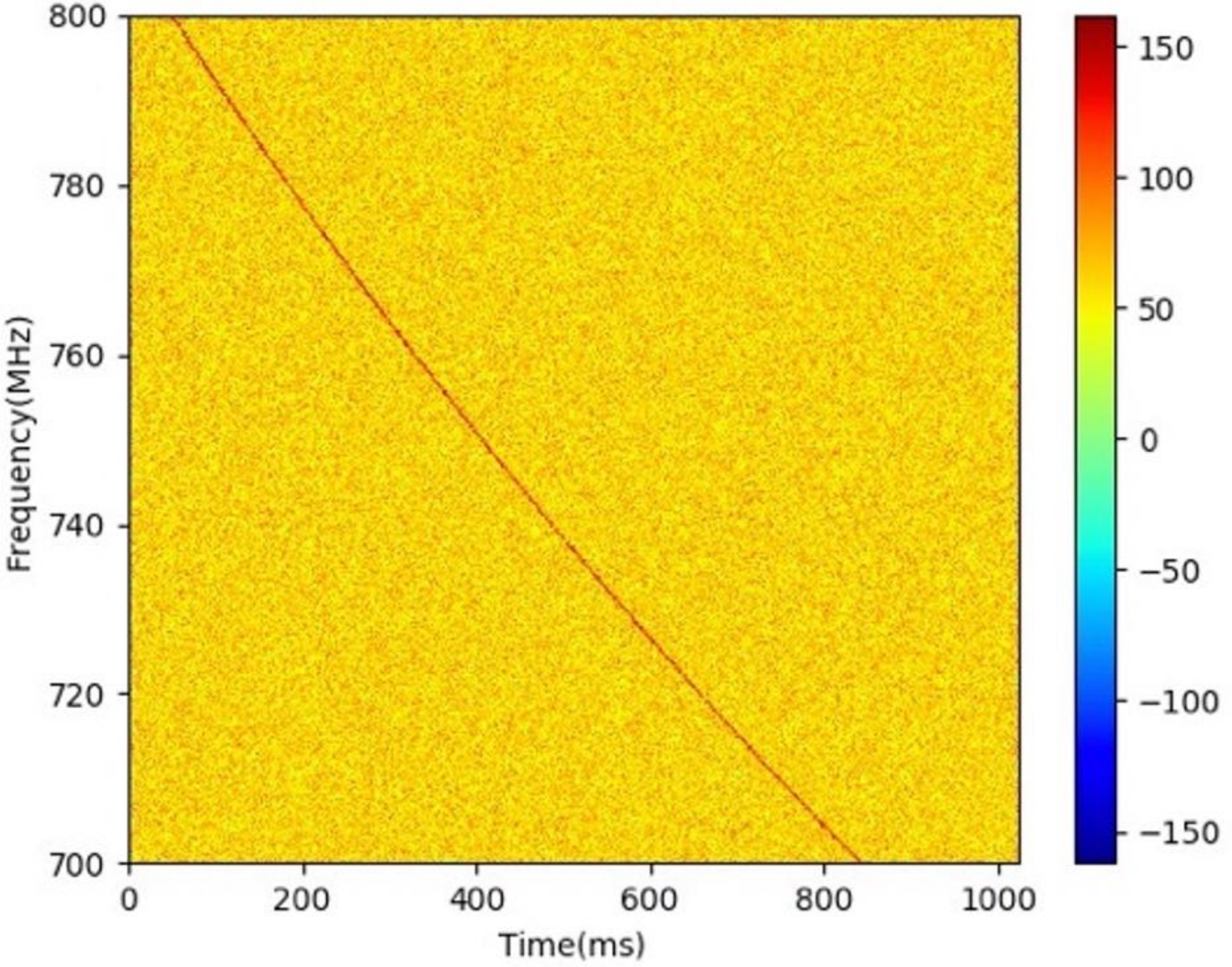
- Straighten the Curve
- 2D-FFT
- Zoom in the burst zone
- Polar Coordinates transform
- 2nd 1-D FFT along radius



Simulated Burst

- **DM : 500** pc cm^{-3}
- **Time resolution : 1 ms**
- **Bandwidth : 700-800MHz**
- **Frequency Channels : 1024**
- **Total Time : 1.024s**

$$-C \cdot DM \cdot \nu^{-2} = -t + t_0 - C \cdot DM \cdot \nu_0^{-2}$$



Straighten The Curve

Denote $\mu = \nu^{-2}$

$$\mu = \frac{1}{\mathrm{C \cdot DM}} \cdot t - \frac{1}{\mathrm{C \cdot DM}} \cdot t_0 + \nu_0^{-2}$$

Slope:

$$k_{re} = \frac{1}{\mathrm{C \cdot DM}}$$

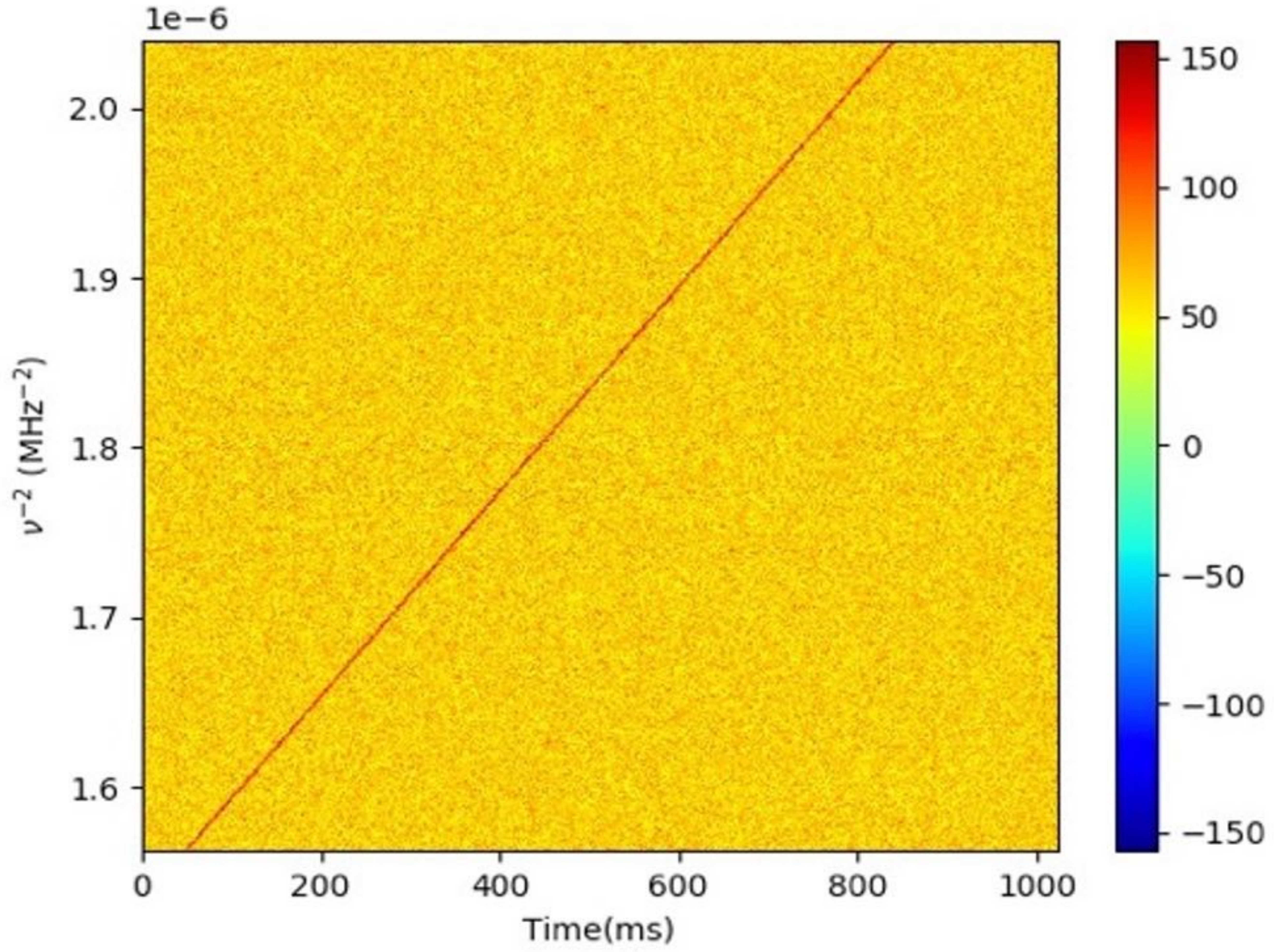
Unit of Slope:

$$\mathrm{Unit_k} = \frac{\mathrm{v_{min}^{-2} - v_{max}^{-2}}}{\mathrm{N_{bin} \cdot T_{sanp}}}$$

Interception of vertical axis:

$$b = -\frac{1}{\mathrm{c \cdot DM}} \cdot t_0 + \nu_0^{-2}$$

Where $t_0 = 50\ \mathrm{ms}$



2D FFT on the straight

In the re-bin map, the curve map could be described as:

$$I(\mu, t) \cdot \delta(k_{rebin} \cdot t + b - \mu)$$

Take Fourier Transfer pair: $(\mu, t) \sim (\omega, f)$, then take 2DFFT:

$$\begin{aligned}
&\mathscr{F}_{\mathbf{2D}}\left\{I(\mu, t) \cdot \delta(k_{re}t + b - \mu)\right\} \\
&= \iint I(\mu, t) \cdot \delta(k_{re}t + b - \mu) \cdot e^{-i2\pi(\omega\mu + ft)}\, d\mu\ dt \\
&= \int I(k_{re}t + b, t) \cdot e^{-i2\pi(\omega(k_{re}t+b)+ft)}\, dt \\
&= \int I(k_{re}t + b, t) \cdot e^{-i2\pi(\omega k_{re}+f)t} \cdot e^{-i2\pi\omega b}\, dt \\
&= I_{total} \cdot \delta(\omega k_{re} + f) \cdot e^{-i2\pi\omega b}
\end{aligned}$$

Transient in (ω, f) plot

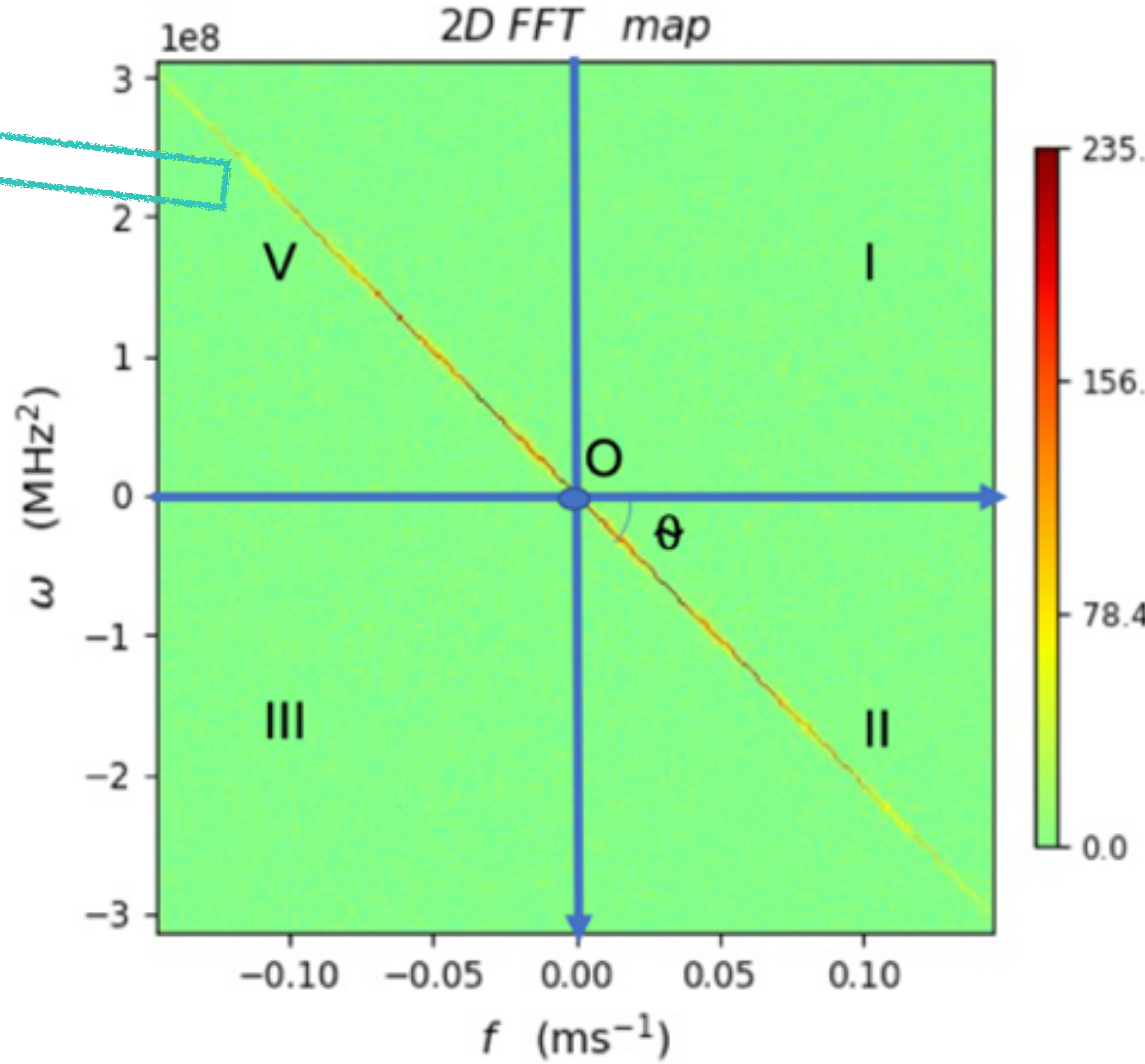
$$I_{total} \cdot \delta(\omega k_{re} + f) \cdot e^{-i2\pi\omega b}$$

In $I(\omega, f)$ plot, The slope of straight is:

$$\omega = -\frac{1}{k_{re}} f$$

And the interception in (μ, t) plot goes to the phase term :

$$e^{-i2\pi\omega b}$$



Transient in (θ, r) plot

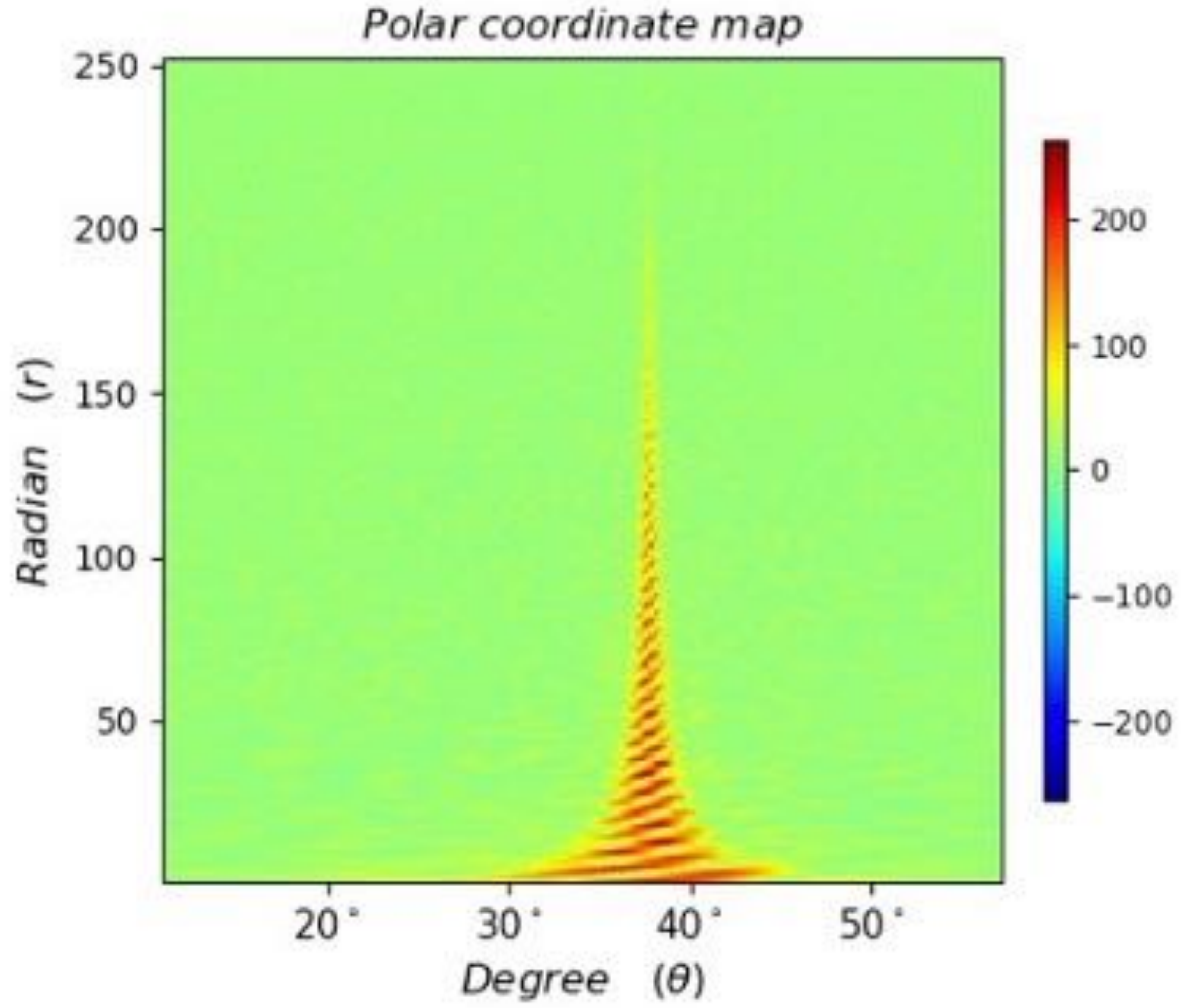
$$\begin{cases} f = r \cdot \cos\theta \\ \omega = N_\omega - r \cdot \sin\theta \end{cases}$$

The standard deviation of 2D matrix of (θ, r) map:

$$\sigma_{2D} = \sqrt{\frac{\Sigma_{i=1}^{N_\theta}\Sigma_{j=1}^{N_r}(I'_{ij} - \bar{I}')^2}{(N_\theta - 1)(N_r - 1)}}$$

Sum along r axis:

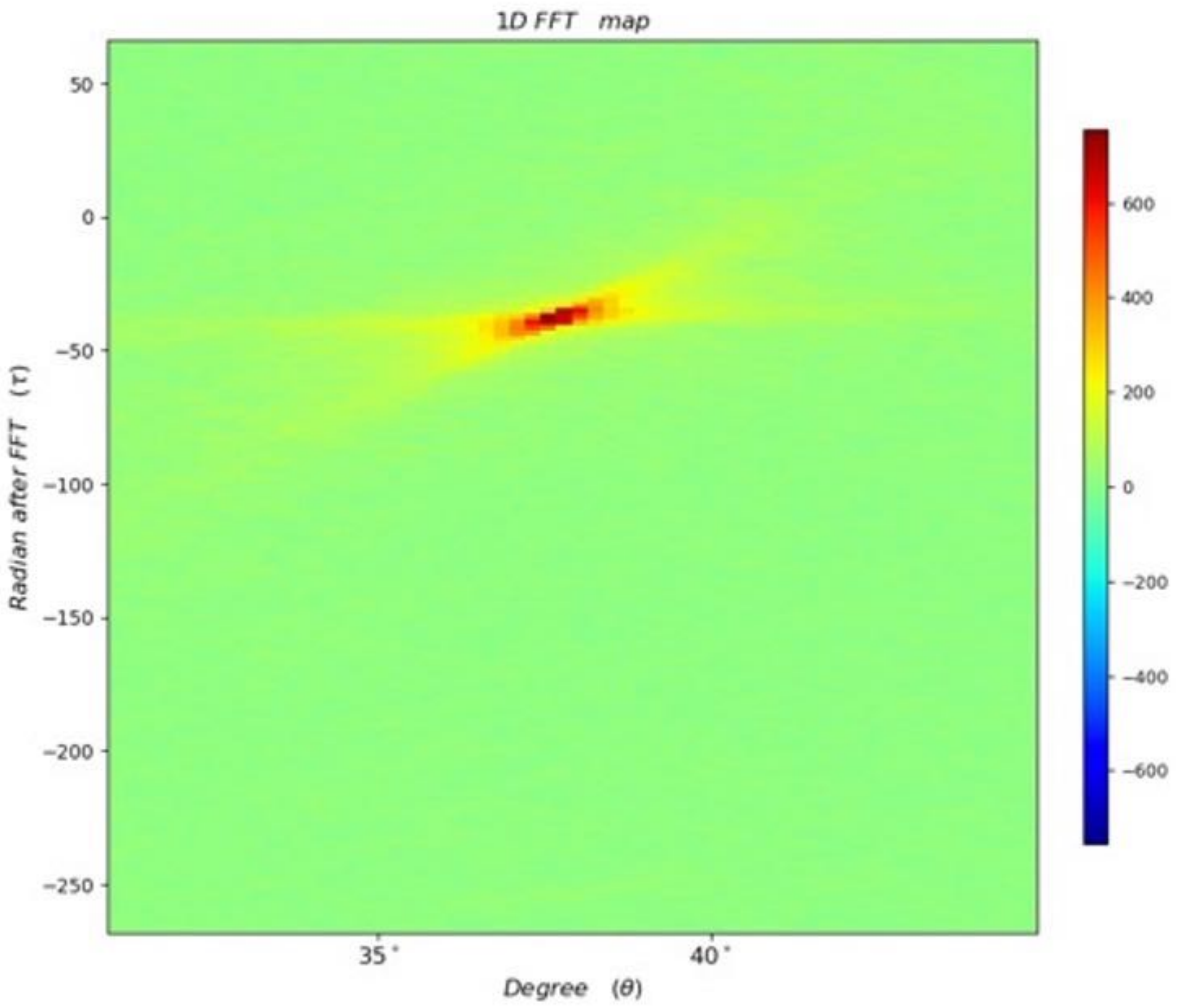
$$\sigma_i = \sqrt{\frac{\Sigma_{i=1}^{N_r}(I'_i - \bar{I}')^2}{(N_\theta - 1)}}$$



The significance after additional 1D FFT

Second 1-D FFT along radian direction, Then the signal converge into some dots.
The amplitude square value of matrix elements contribute to χ^2 distribution with degree 2. Pick the singular values from the spots. Then calculate the significance as:

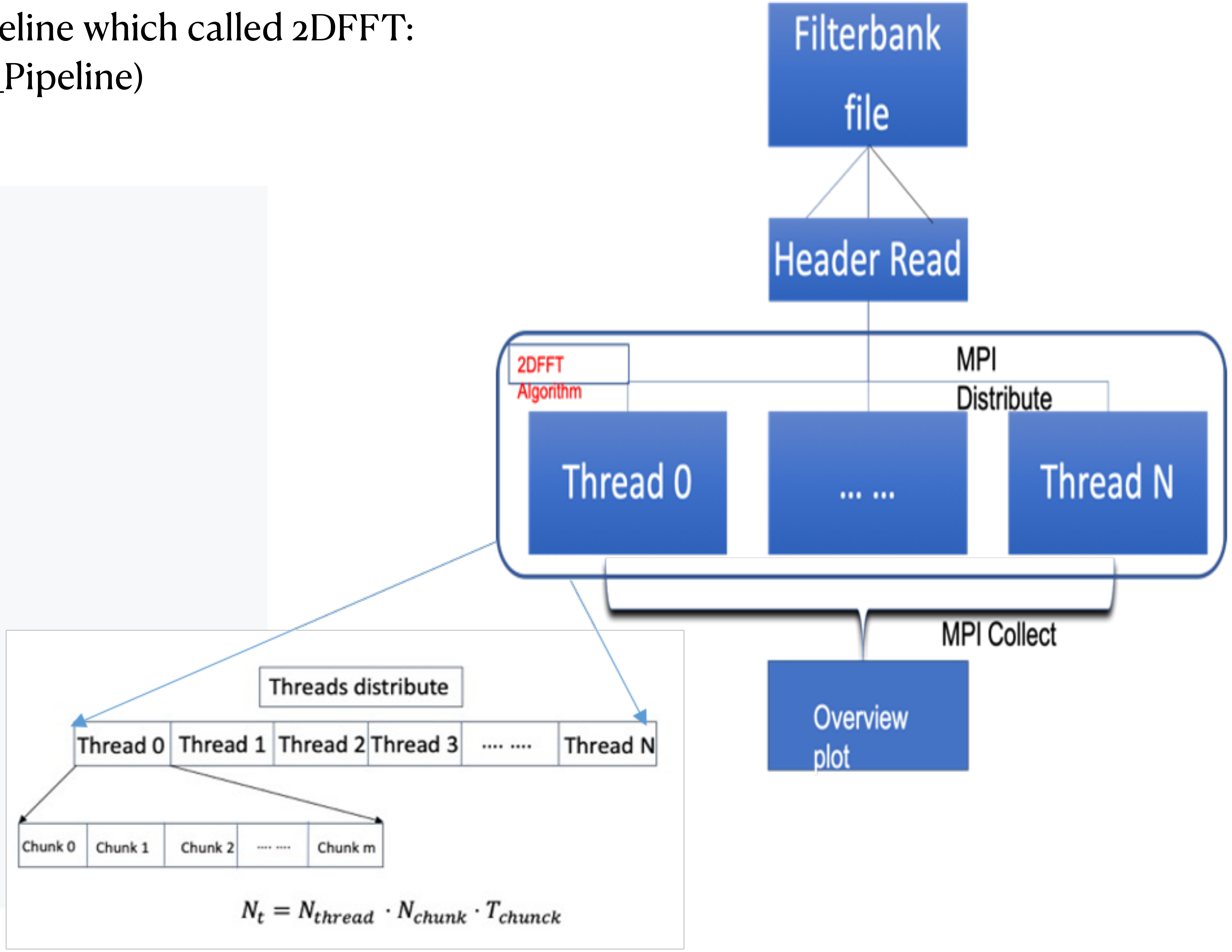
$$r_{sig} = \sum_{\Delta\theta} \frac{|I(\tau, \theta)|^2_{\geq T_\sigma})}{\sigma \cdot N_{pixel}}$$



2DFFT Pipeline

Based on this algorithm we developed a open source pipeline which called 2DFFT: (https://github.com/peterniuzai/2DFFT-transient_search_Pipeline)

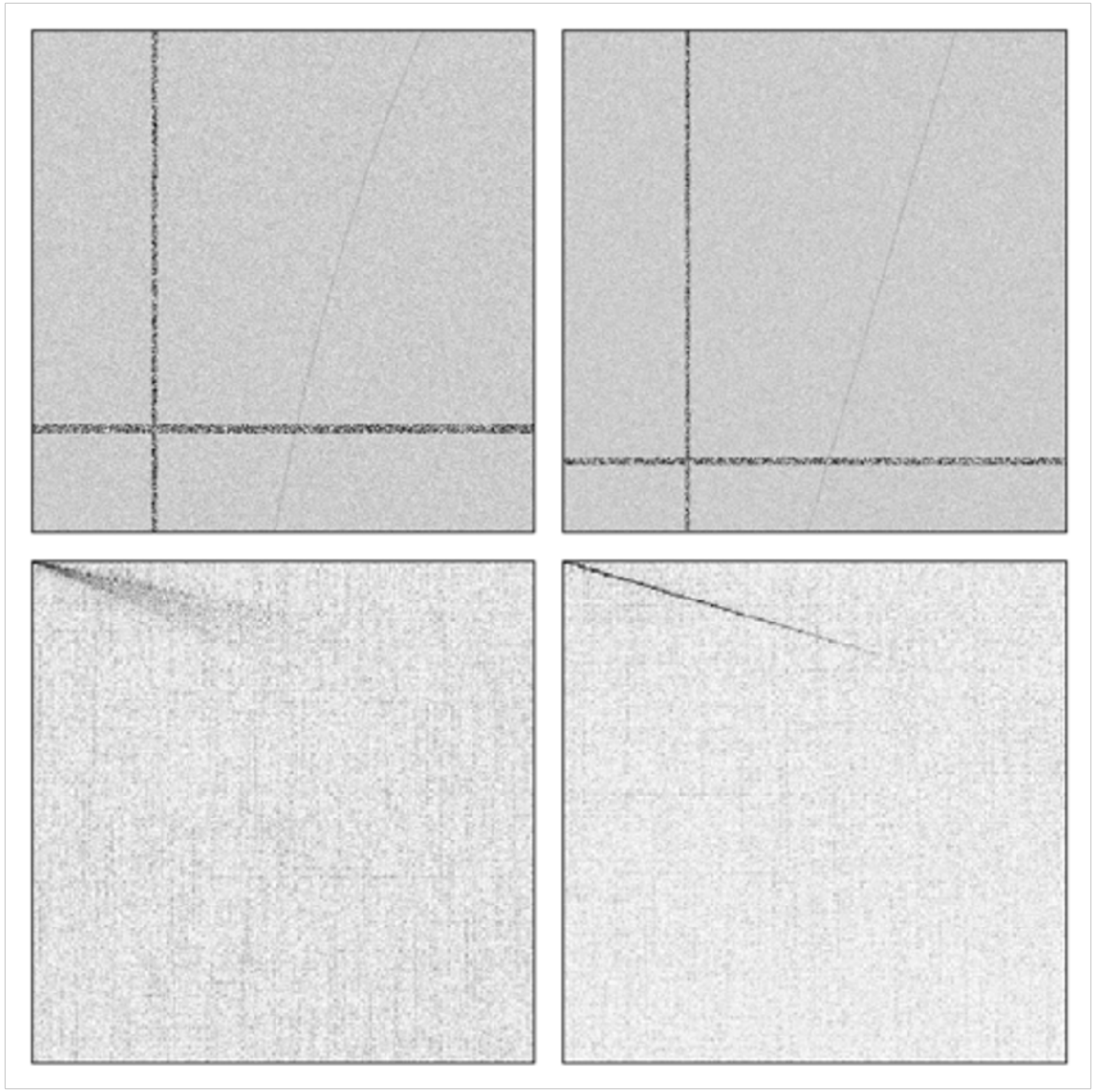
```
 python __main__.py -h:

Usage: mpirun -n <number of processor> python __main__.py  [options]
Options:
  -h, --help show this help message and exit
  -f FILE, --file=FILE Put filterbank file want to search
  -t THRESHOLD, --threshold=THRESHOLD
                        Threshold(sigma) for candidates pick
  --dm=DM               Set  DM range, Suggest use default [50,2000]
  --pixel=PIXEL         Pixels number at 2nd 1DFFT map
  --mask_cycle=MSK_CYCLE
                        Mask abnormal lines at 1st 2DFFt map, only when RFI is
                        terrible
  --nsamps_gulp=T_LEN   Samples number for onece process, suggest use self-
                        calculate(def)
  --nbin=NBIN           number of channels after re-bin step, suggest use
                        self-calculate(def)
  --wp=WP               Set width of pulse to search, Suggest use default
                        10(ms).
  --angle=ANGLE         Angle range within [0,90], For de-buging.
  -v, --verbose         Show details of process
  -p, --plot            Make overview plot for final result
  --Plot_proc=PLOT_PROC
                        Input process step key words want to make signle plot.
                        Key words Including:  {raw, rebin, 1stFFT,
                        polar_sets_3D, polar_sets_2D, 2ndFFT_3D, 2ndFFT_2D}
                        (This function Remain updates)
```



Better at large scale RFI eliminating

Top panels: Left and right plots the transient waterfall with and without pre-process.

Bottom panels: Perform 2D FFT on the transients with and without the pre-process.



Results:

- After 2DFFT, The transient divergence with pre-process is much smaller than that without pre-process.
- The large scale RFI could be eliminated clearly after 2DFFT.

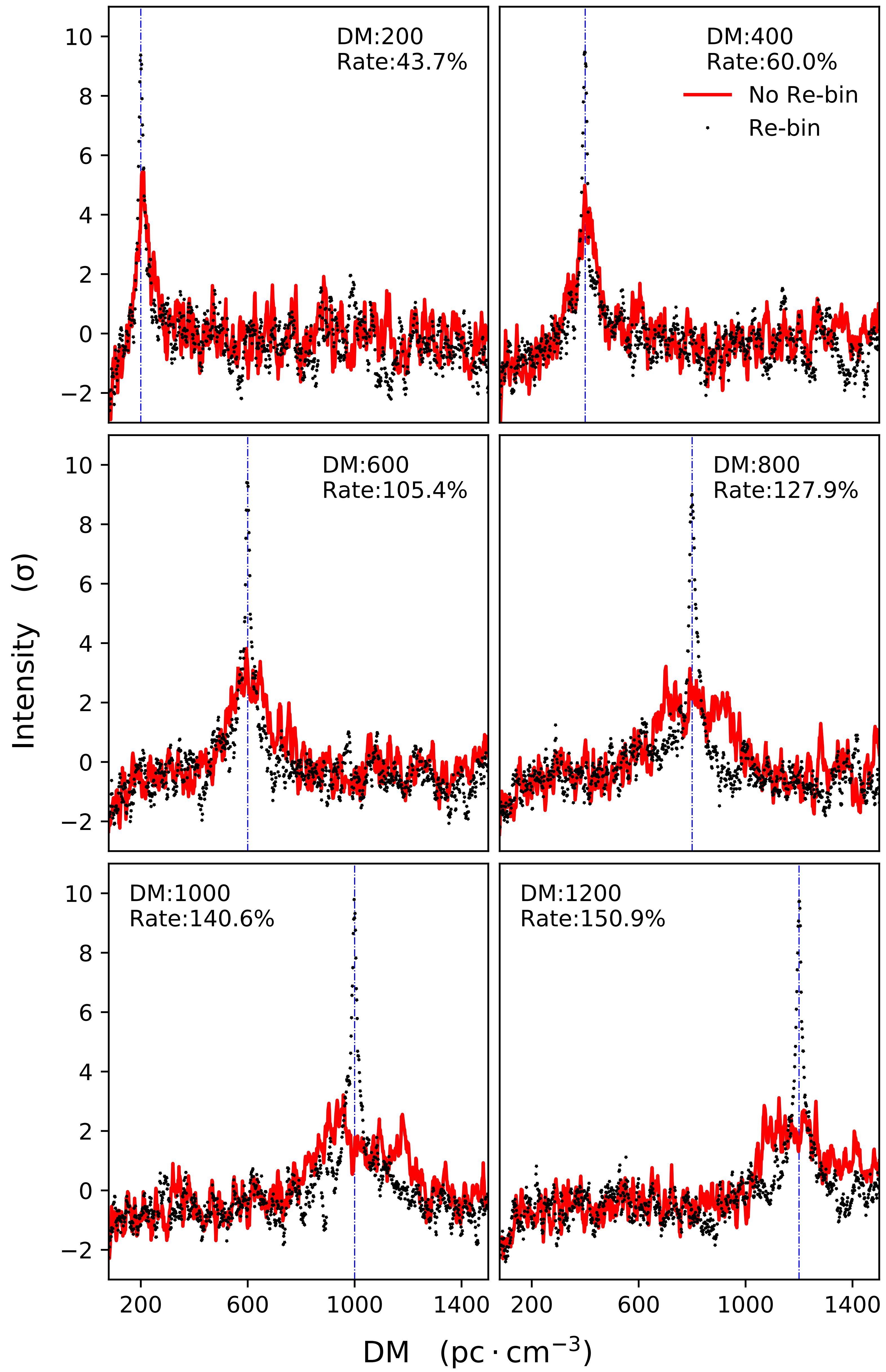
The S/N improvement after re-bin process

Time resolution : 1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : 4096

$$S = (I_{max} - I_{mean})/\sigma$$
$$\mathscr{R} = (S_{rebin} - S_o)/S_o$$

Results:

- The S/N improvement Varied with DM. (Curvature)
- Due to the large DM of FRB, Re-bin process is necessary to be taken in use.

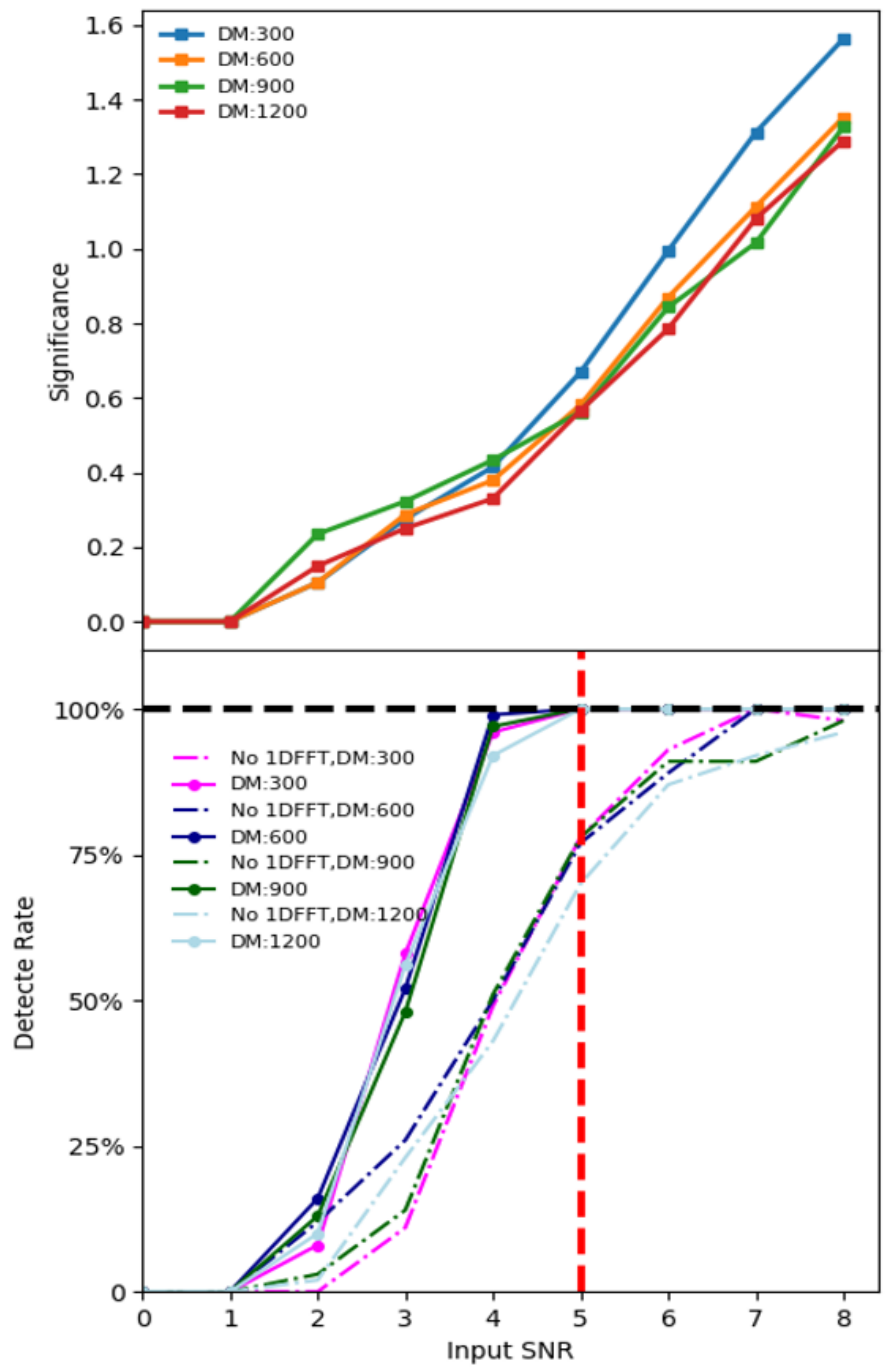


The detection rate after additional 1D FFT

Time resolution : 1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : 1024
Inject different DM transients
Each DM are generated 100 times.

Results:

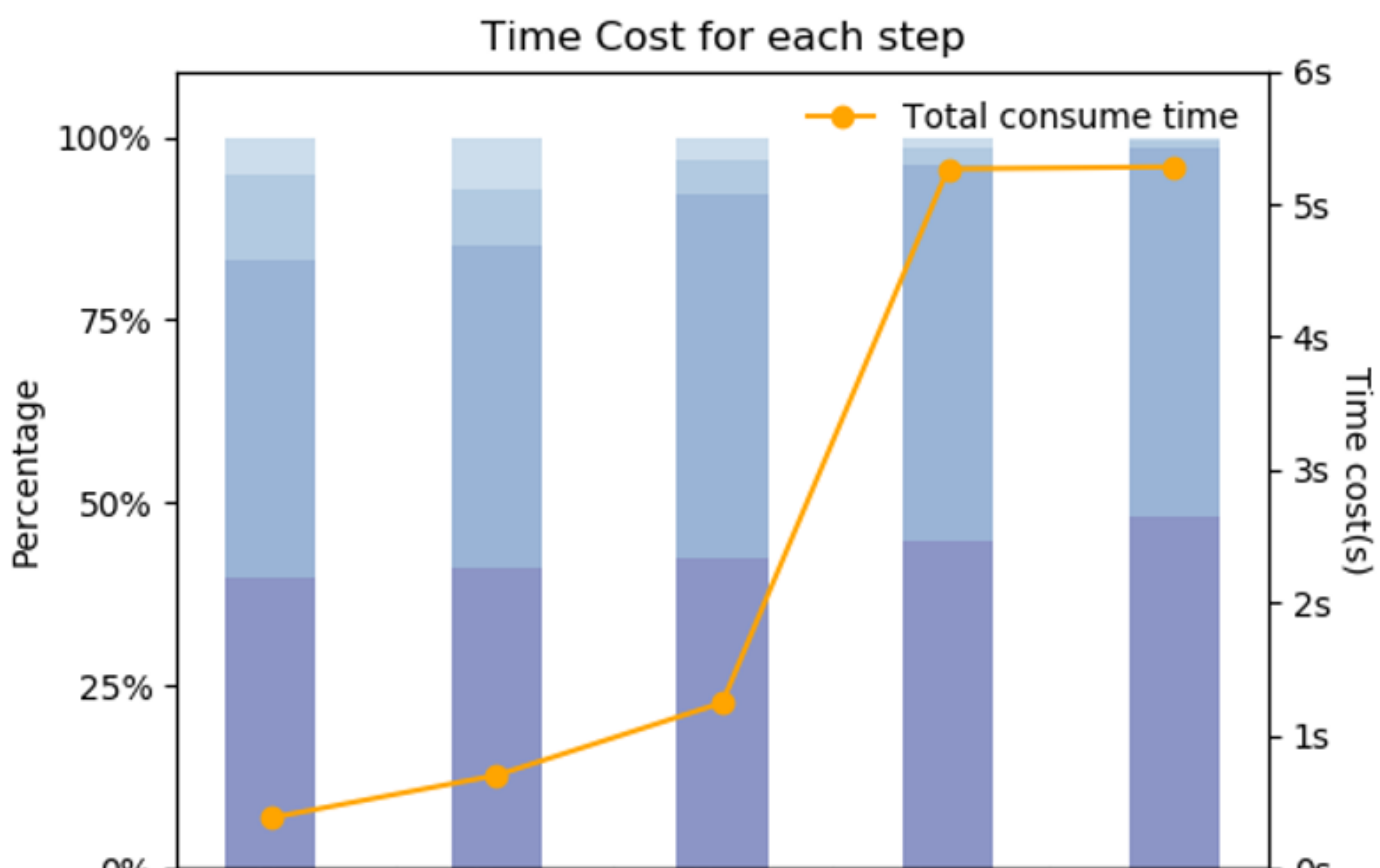
- Result: With additional 1DFFT, the detection sensitivity could reach 100% when input SNR is 5.
- Additional 1D FFT is necessary and helpful to improve the detection rate.



Time cost of each step

Time resolution : 1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : ?

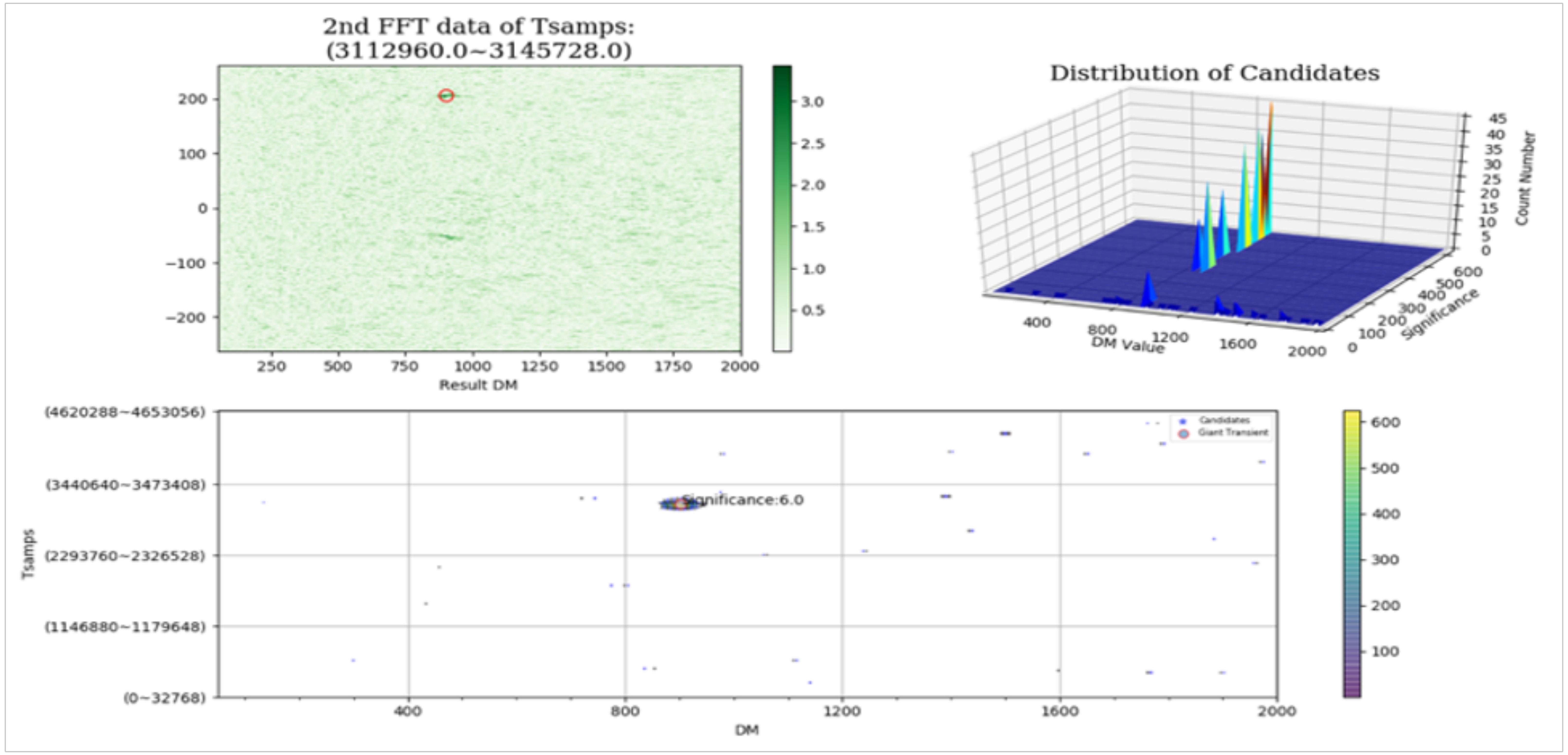
Results:
- 2DFFT and re-bin step cost a lot in this algorithm
- The other steps are acceptable



	N_{128}	N_{256}	N_{512}	N_{1024}	N_{2048}
1DFFT	5.26%	7.00%	3.29%	1.42%	0.34%
Polar	11.58%	8.00%	4.41%	2.36%	1.17%
2DFFT	43.42%	43.86%	50.00%	51.48%	50.51%
Re-bin	39.74%	41.14%	42.30%	44.74%	47.97%

Exam the known FRBs

FRB name	$n_t \times n_f$	Data Duration(m)	Process time(m)	SNR	Width(ms)	DM	DM Found
FRB140514	14438400 × 1024	15.4	6.8	16	2.8	562.7±0.6	567.96
FRB010125	2121728 × 96	4.4	5.5(s)	17	9.4	790±3	799.21
FRB010621	8400896 × 96	35.0	0.38	16.3	7	745±10	747.89
FRB090625	4620288 × 1024	4.9	2.23	30	1.92	899.55±0.01	897.03
FRB130729	4554752 × 1024	4.9	2.1	14	15.61	861±2	860.46
FRB130628	4587520 × 1024	4.9	2.2	29	0.64	469.88±0.01	470.46
FRB130626	4587520 × 1024	4.9	2.1	21	1.98	952.4±0.1	951.88
FRB110220	4489216 × 1024	4.8	2.1	49	5.6	944.38±0.05	945.78
FRB110523	55296 × 4096	56.62(s)	5.18(s)	42	1.73	623.3±0.06	627.26

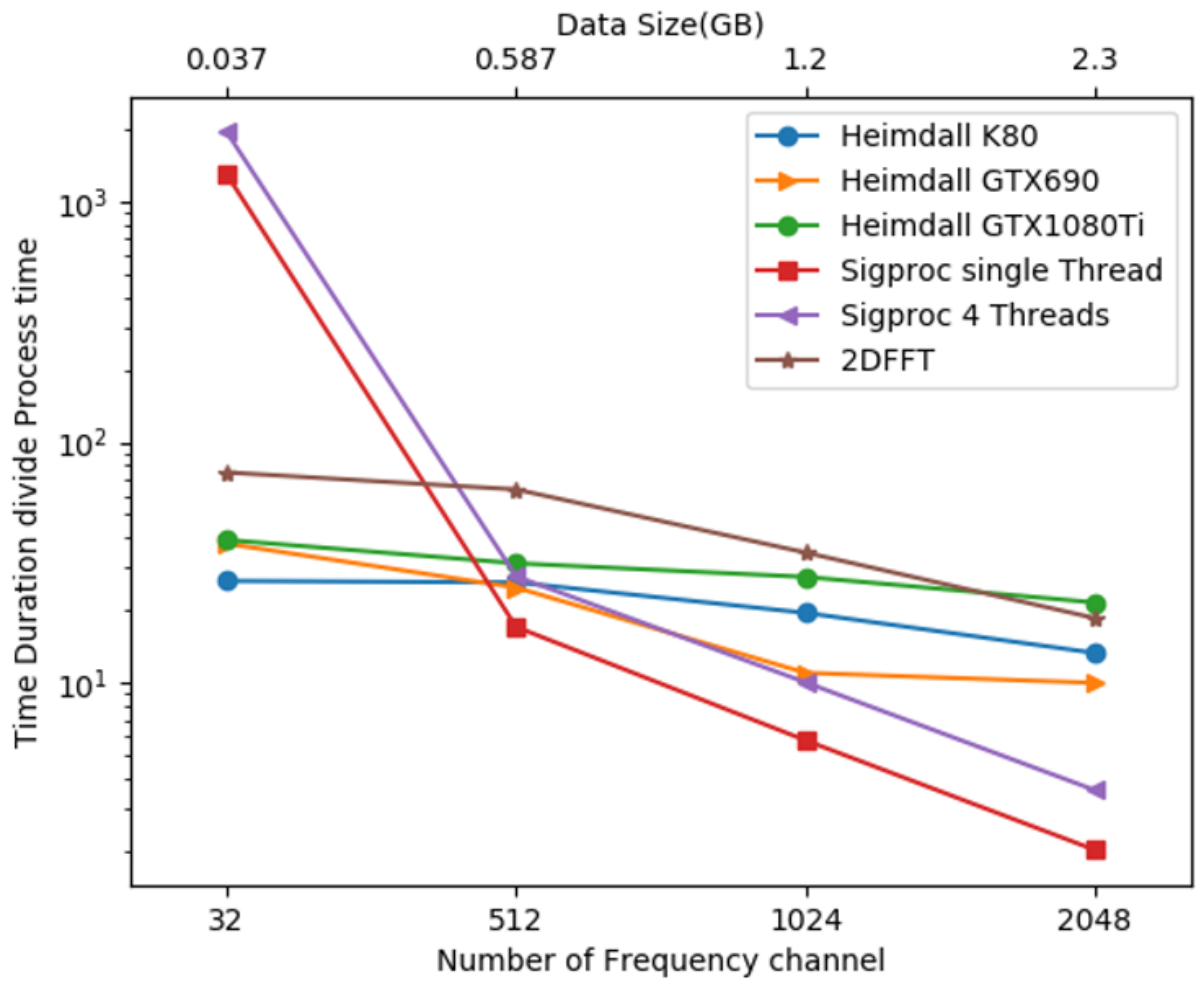


Compare with Other Open Source Software

Time resolution : 1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : -?
Total Inject time duration: 1200 s

Software list:

- Heimdall (GPU based)
- SIGPROC (Single and multi Treads)
- SIGPYPROC
- 2DFFT (4 Threads)

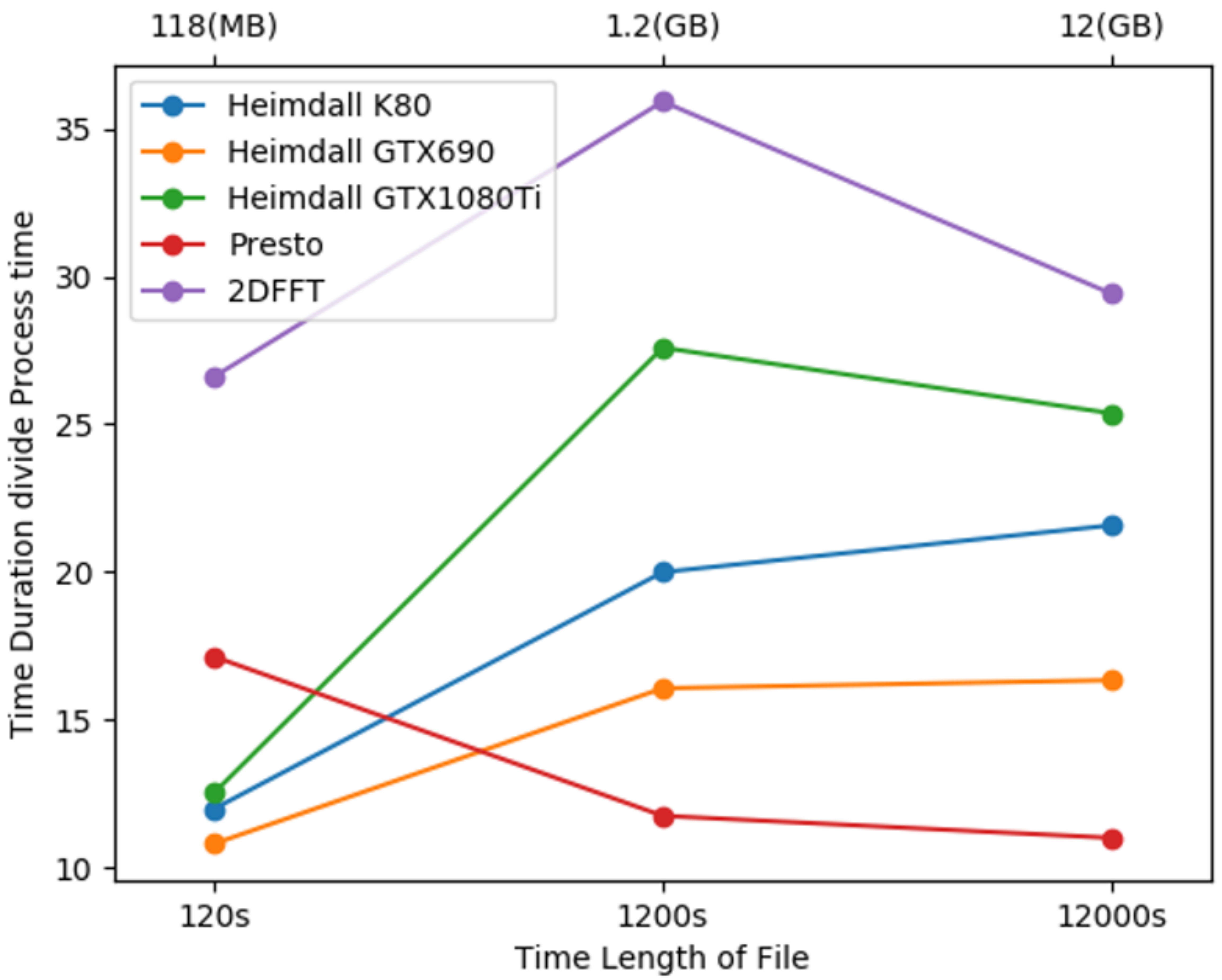


Compare with Other Open Source Software

Time resolution : 1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : 1024
Total Inject time duration: -?

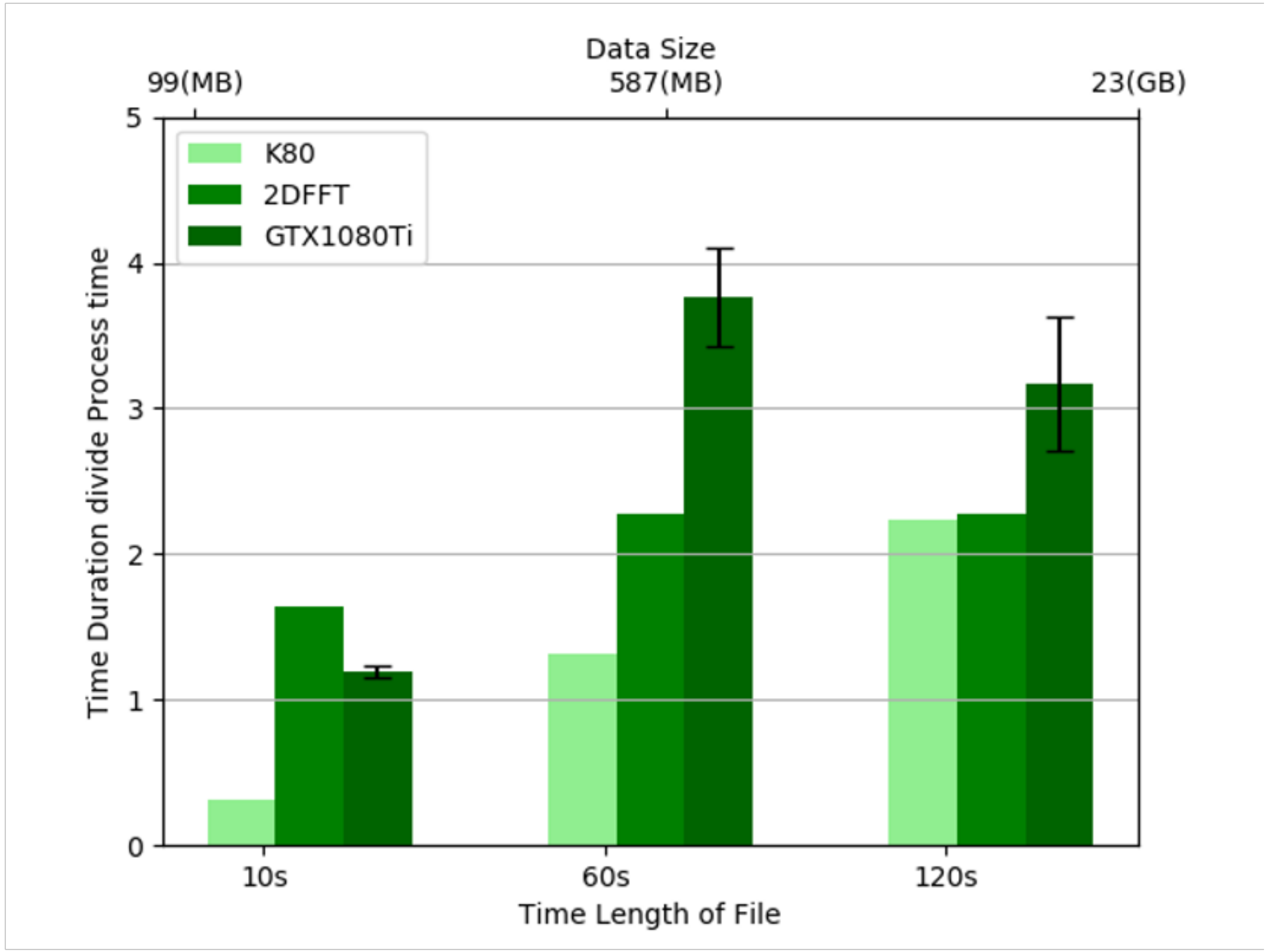
Software list:

- Heimdall(GPU based)
- PRESTO (Sub-band)
- 2DFFT(4 Threads)



Compare with Other Open Source Software

Time resolution : 0.1 ms
Frequency Bandwidth: 700-800 MHz
Number of frequency Channels : 2048
Total Inject time duration: -?



Software list:

- Heimdall(GPU based)
- 2DFFT(4 Threads)

Conclusion & Future

2DFFT is a highly effective pipeline for searching radio transients. It excels at eliminating radio frequency interference (RFI) and parallel processing. Although the time cost of the re-bin step could not be ignored, the pipeline based on GPU is also promising.

Our collaborators from Computer Network Information Center (CNIC) have created a GPU-accelerated 2DFFT pipeline. This pipeline has the capability to achieve twice the speed of our Python version. More information regarding the specifics will be provided soon.