The Highest Time-Resolution Measurements in Radio Astronomy: The Crab Pulsar Giant Pulses

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Extreme Astrophysics in an Ever-Changing Universe

16-20 June, 2014

Acknowledgments

Jim Cordes	Cornell University
Jared Crossley	New Mexico Tech, NRAO
Tracey Delaney	New Mexico Tech, WV Wesleyan
Jean Eilek	New Mexico Tech, NRAO
Glenn Jones	Cal Tech, NRAO
Jeff Kern	New Mexico Tech, NRAO
Mark McKinnon	New Mexico Tech, NRAO
David Moffett	New Mexico Tech, Furman University
Jim Sheckard	New Mexico Tech
Jim Weatherall	New Mexico Tech, FAA

Staffs of NRAO and NAIC

Science objectives

- What is the pulsar radio emission mechanism?
- How does a relativistic magnetized pair plasma radiate at equivalent brightness temperatures of $10^{36} - 10^{42}$ K?
- Can we understand Crab Nebula pulsar?

  Does the Crab fit the canonical pulsar model?

  Or is it unique?

Summary

Time resolution down to 0.2 nanoseconds achieved using a large-memory digital oscilloscope and coherent dedispersion

Scientific Method:

Form Hypothesis:

Emission is a form Shot noise: Cordes, 1976

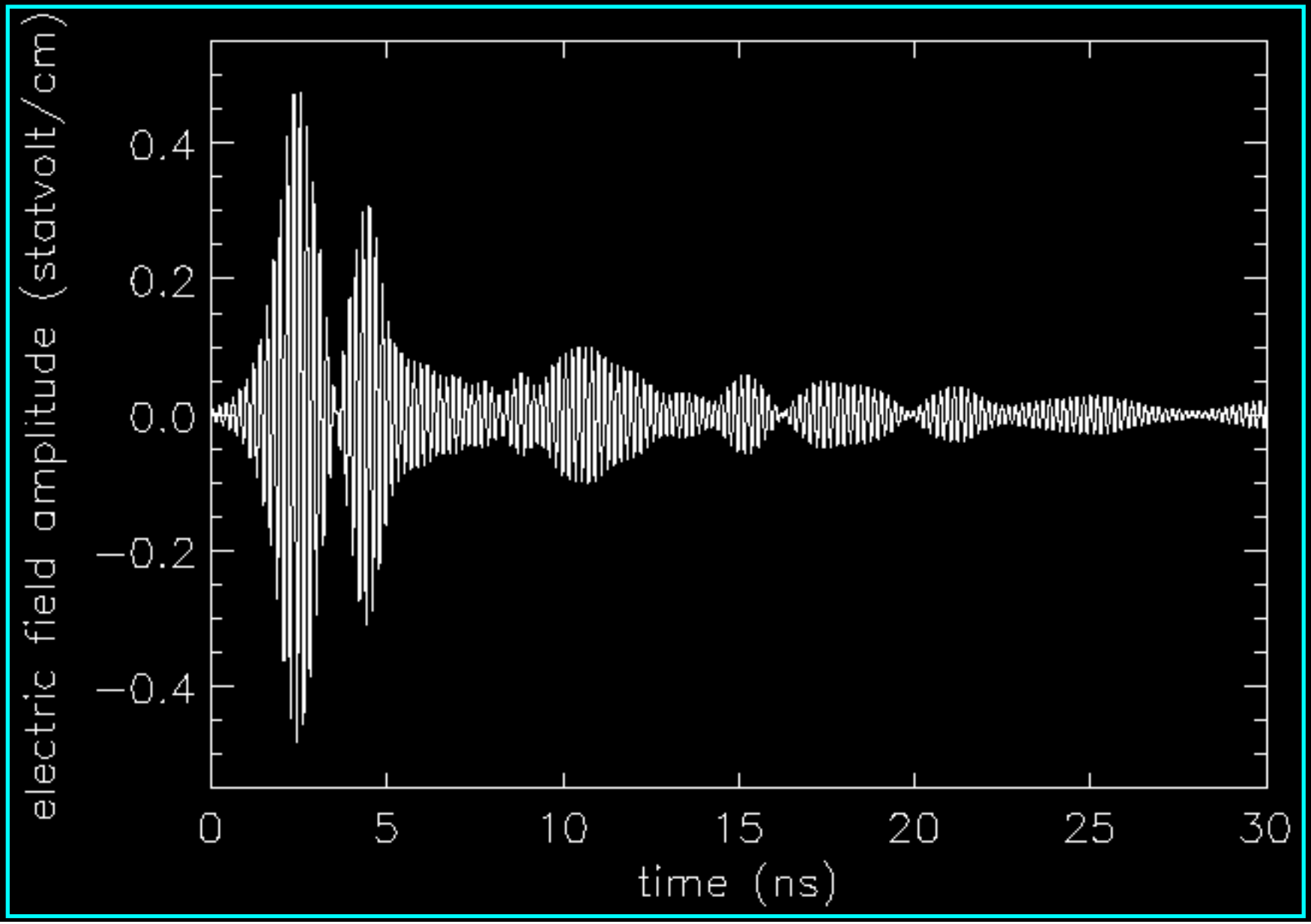
Make predictions:

Shot noise cause: Collapsing solitons in turbulent plasma: Weatherall, 1998

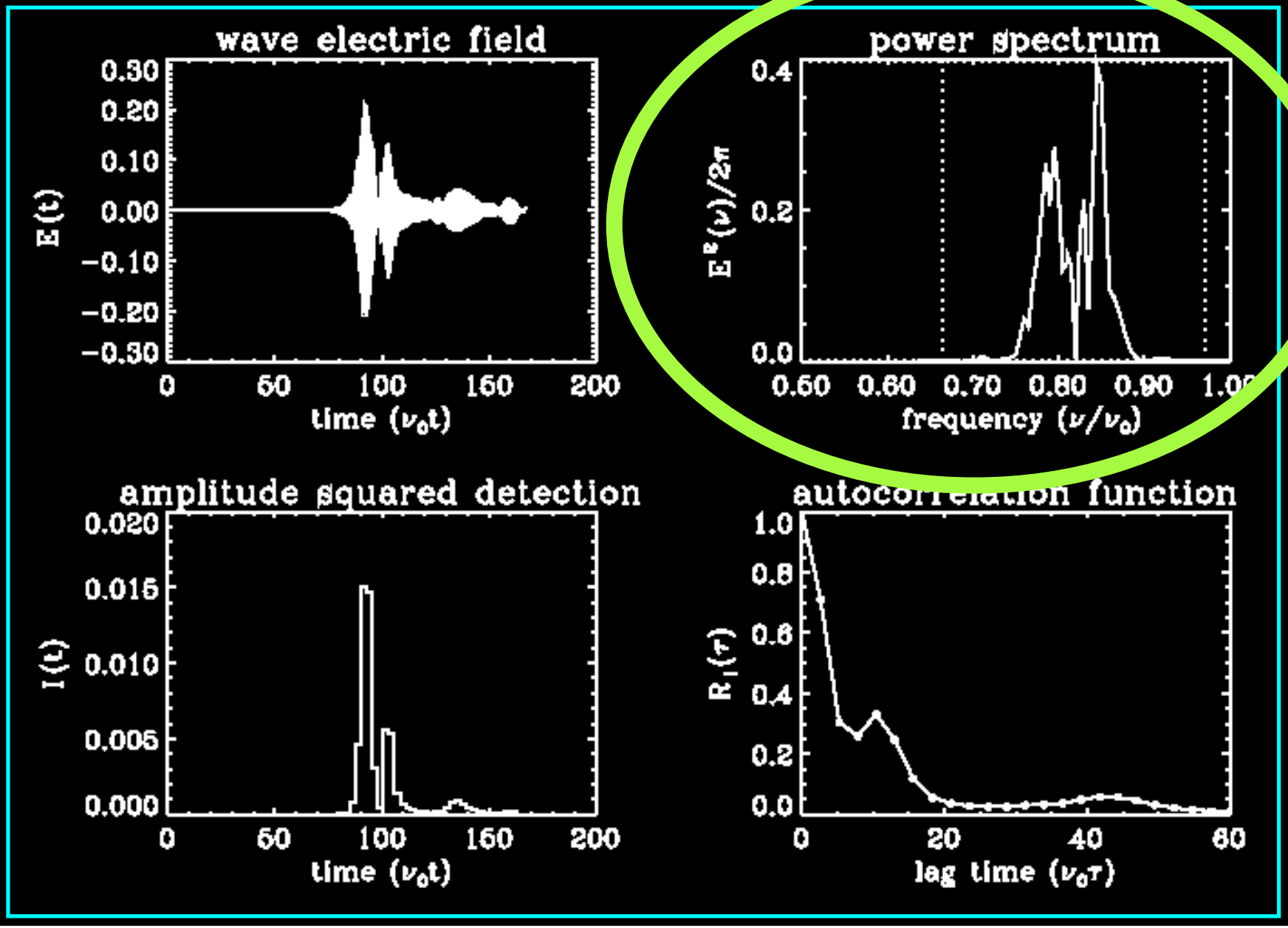
Test by experiment:

High-time resolution observations

Collapsing soliton prediction I



Prediction II



How to get high time resolution:

Coherent dedispersion required.

- **Sample receiver *voltage* at Nyquist rate.**
- **Pass signal through a filter with the inverse dispersion characteristic of the Interstellar Medium.**
- **Use square-law detectors to obtain intensity.**

(Polarization slightly more complex.)

Coherent dedispersion

- **Emitted signal:** $s(t) \Leftrightarrow S(\omega)$
- **Dispersive ISM:** $H(\omega) = \exp[ik(\omega)z] \Leftrightarrow h(t)$
- **Received signal:** $s(t)*h(t) \Leftrightarrow S(\omega)\,H(\omega)$
- **Dedispersion processing:** $S(\omega)H(\omega)\cdot H(\omega)^{-1} \Leftrightarrow s(t)$
  - » and 10,000 lines of code

$\Leftrightarrow$: Fourier Transform

$*$: Convolution

What Can You Do With It?

Diagnostic for emission mechanism studies:

Found nanostructure predicted by Weatherall

Propagation studies:

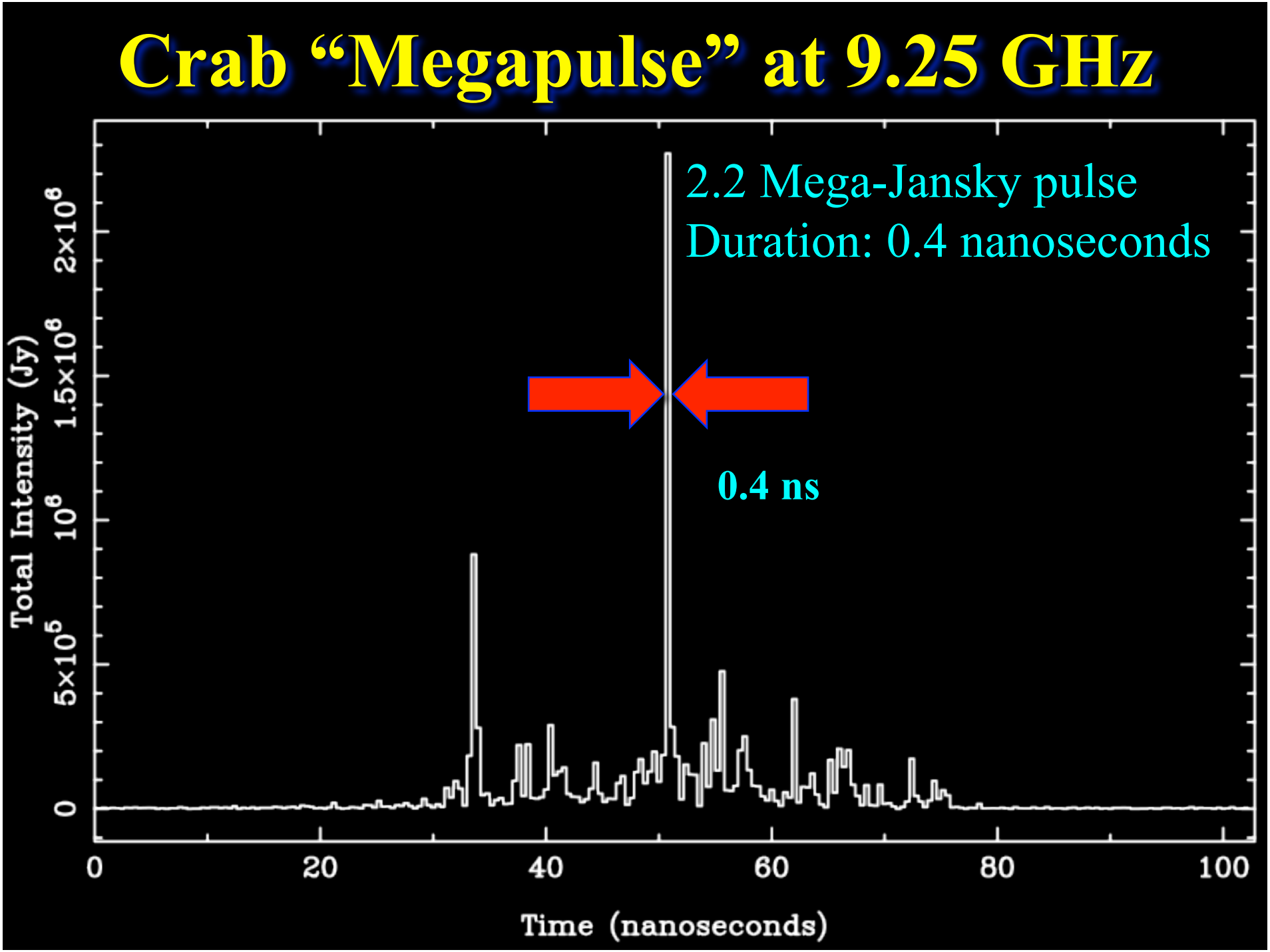
Precision DM determination

Discoveries:

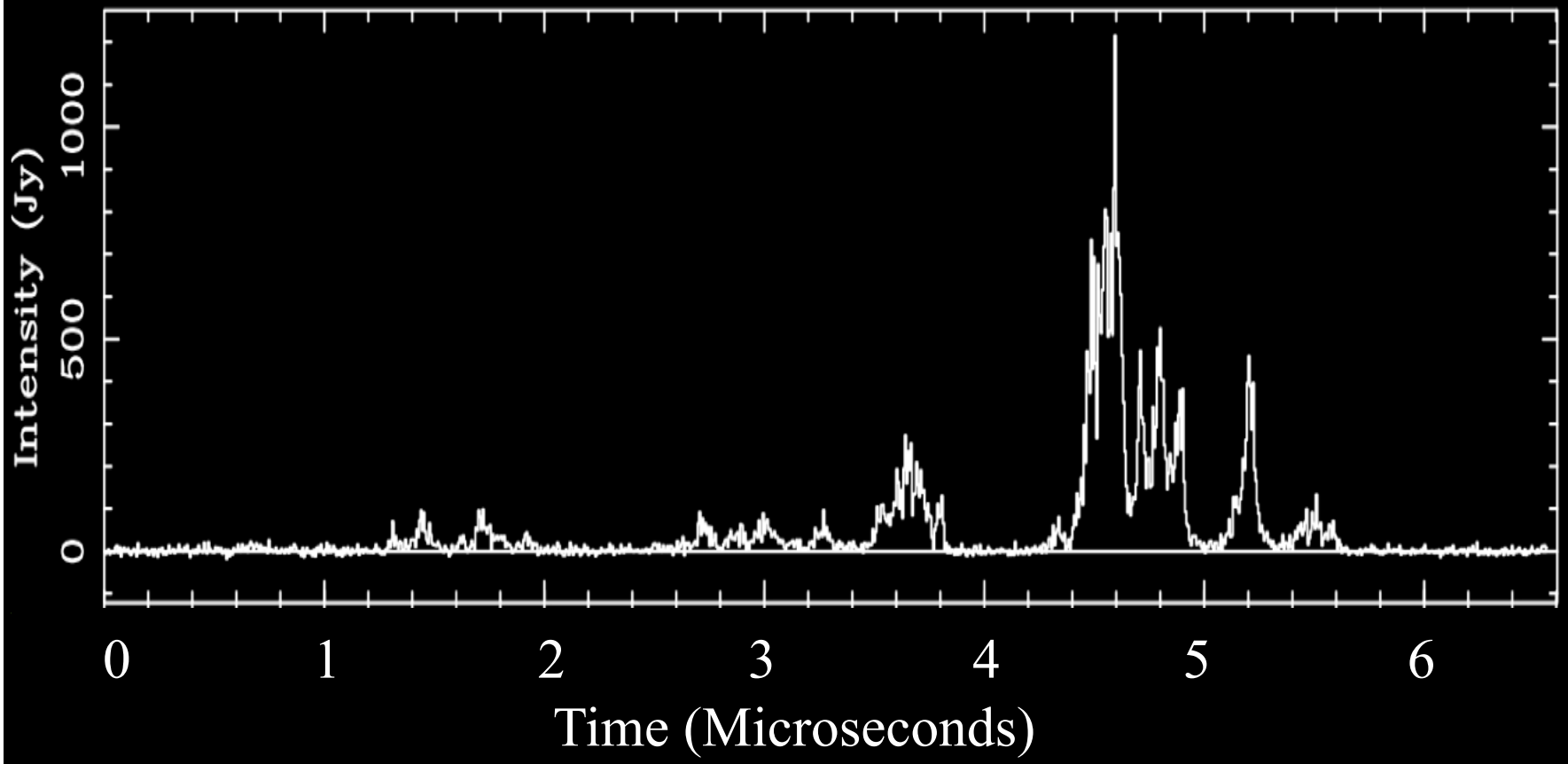
Echoes of Crab “giant” pulses

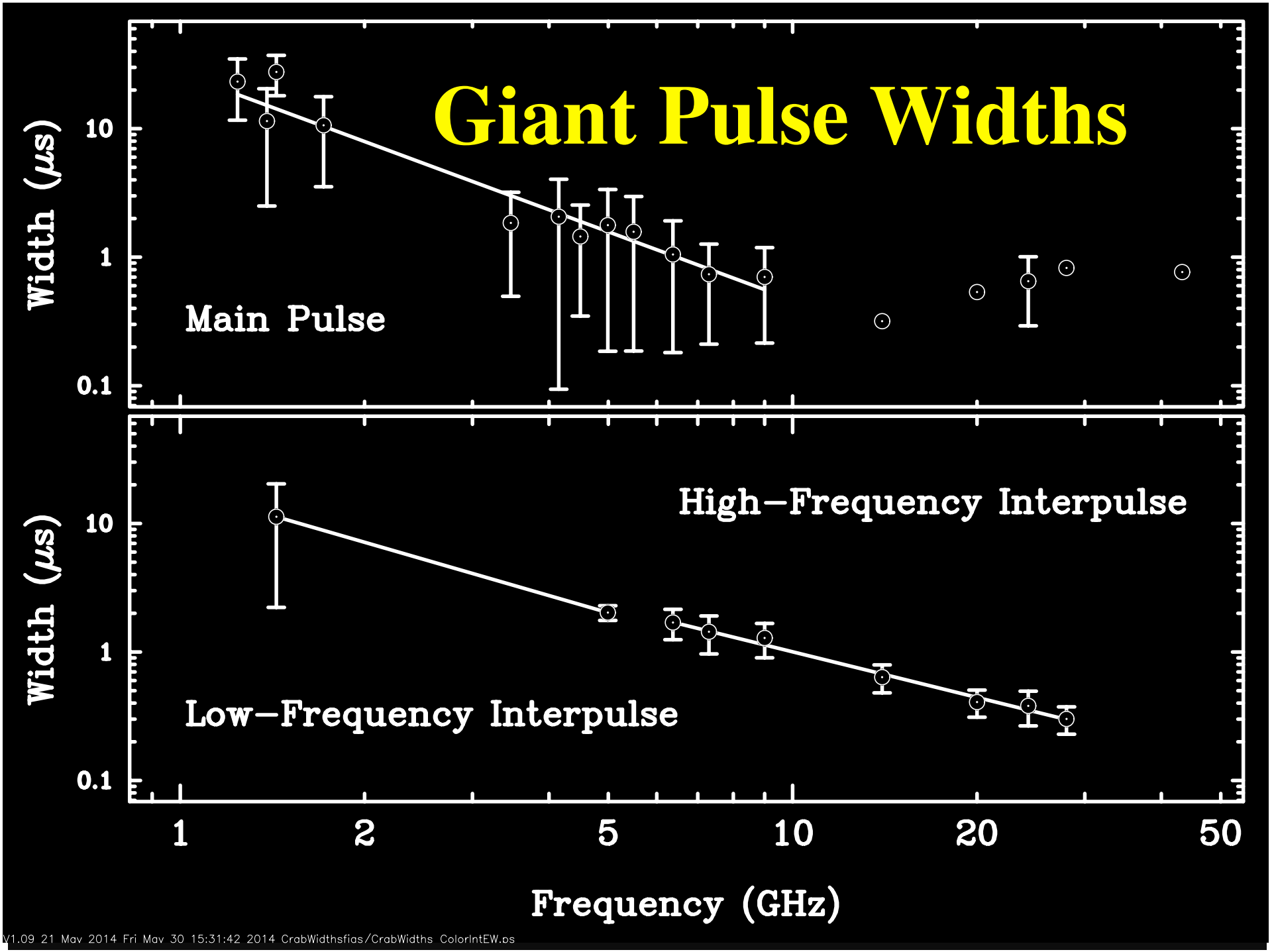
Crab Interpulse spectral bands

Crab "Megapulse" at 9.25 GHz



Not all pulses are so short
Typical Main Pulse, 9 GHz




Giant Pulse Widths
Width (μs)
10
1
0.1
Main Pulse
High−Frequency Interpulse
Low−Frequency Interpulse
1
2
5
10
20
50
Frequency (GHz)
V1.09 21 May 2014 Fri May 30 15:31:42 2014 CrabWidthsfias/CrabWidths ColorIntEW.ps

Dispersion Measure Determination Methods:

Time delay between two frequencies

- Must account for pulse shape change & Scattering broadening

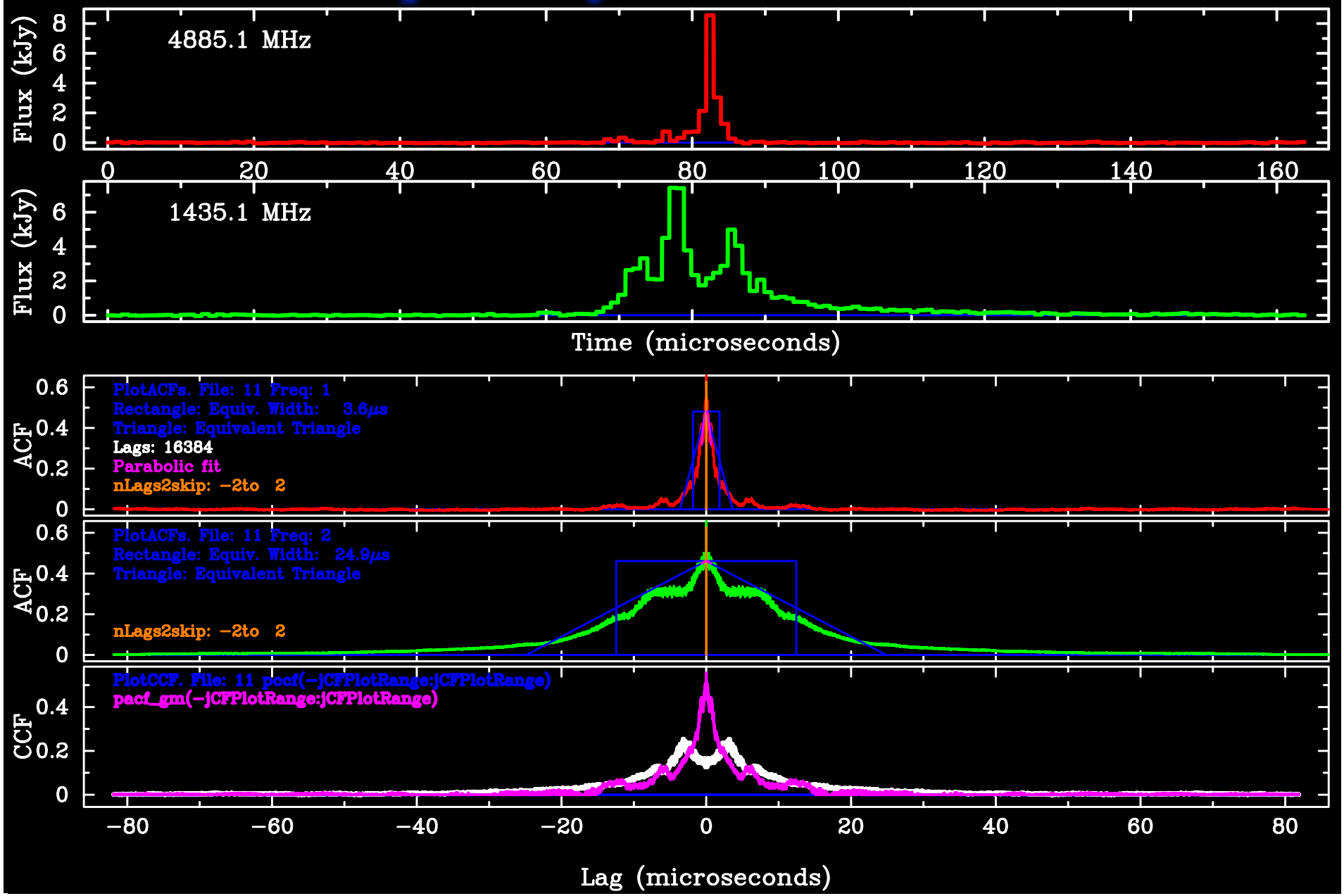
Split receiver passband

- Cross-correlate micro-, nanostructure

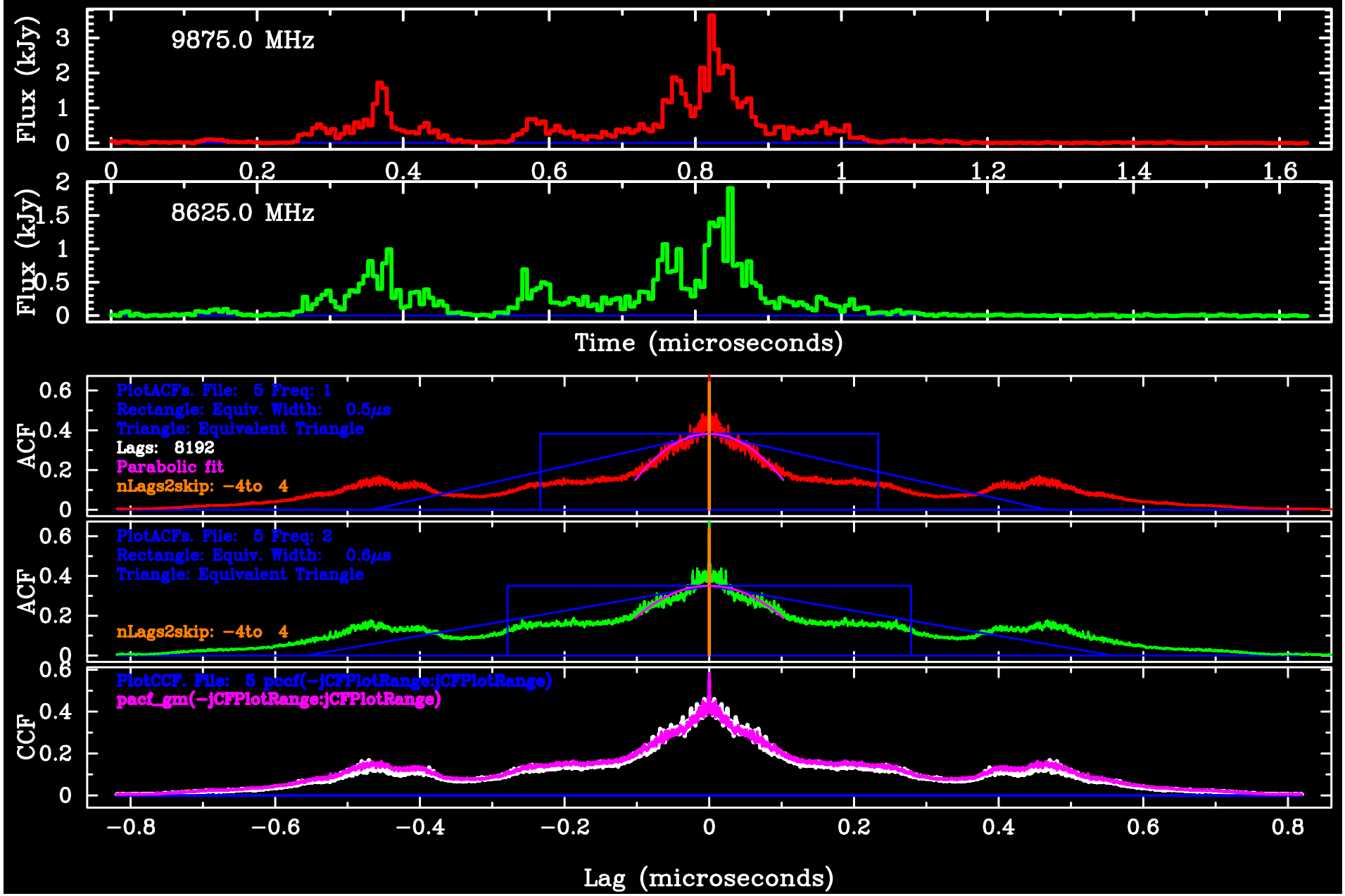
Adjust dispersion removal filter to

- Maximize pulse intensity variance
- Minimize equivalent width

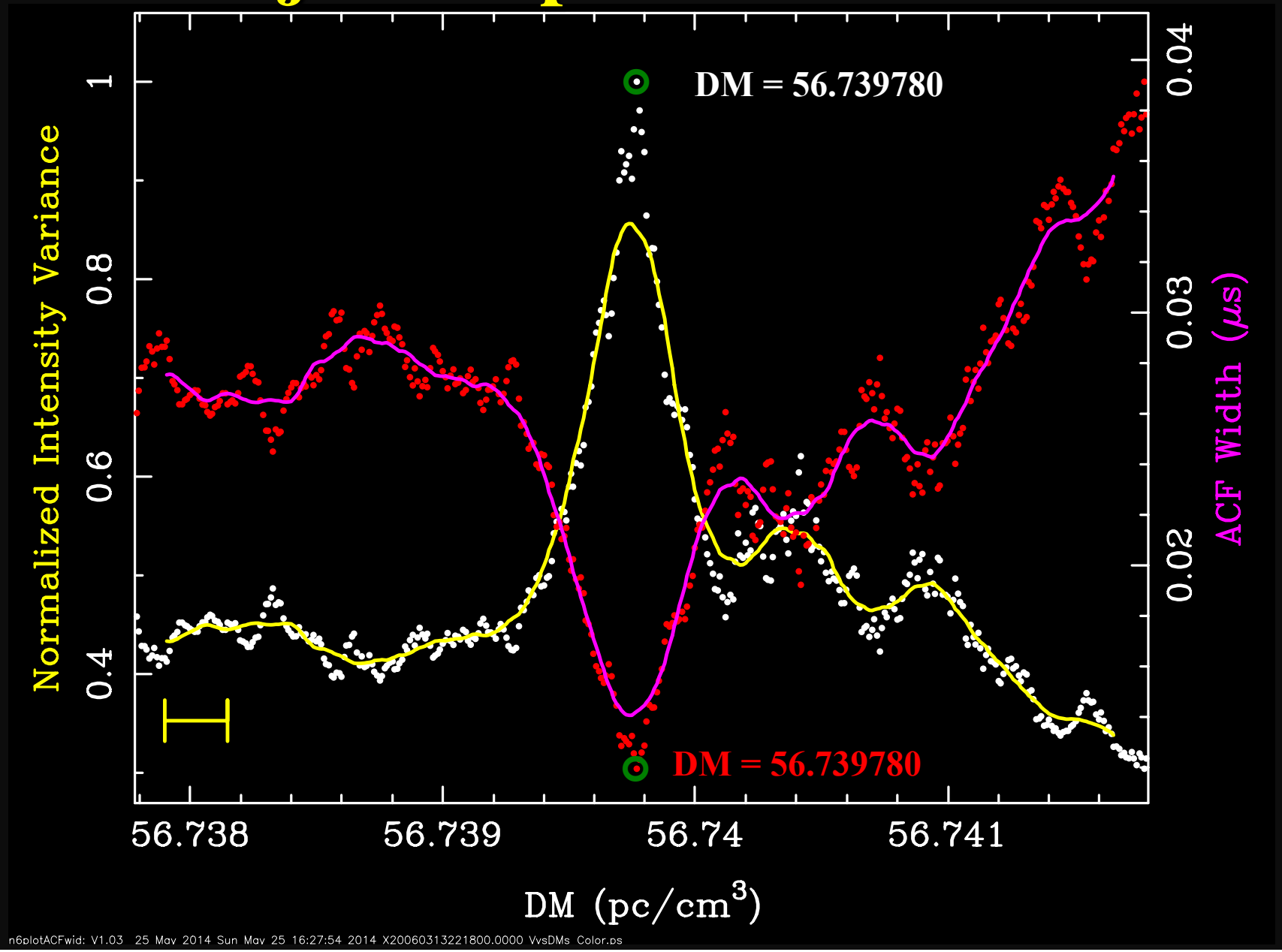
Two-frequency Cross-correlation



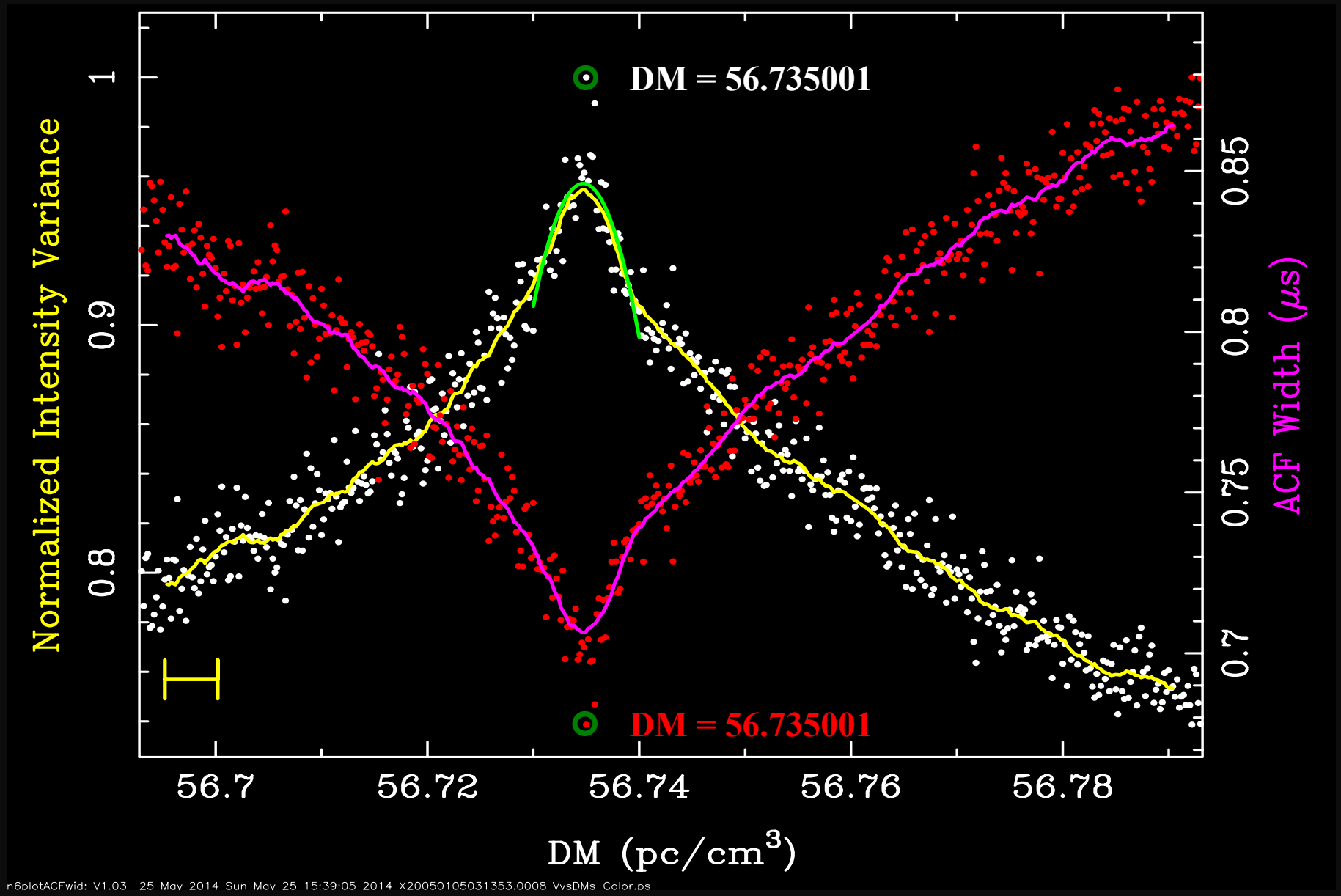
Split-band Cross-correlation



Adjust Dispersion Measure



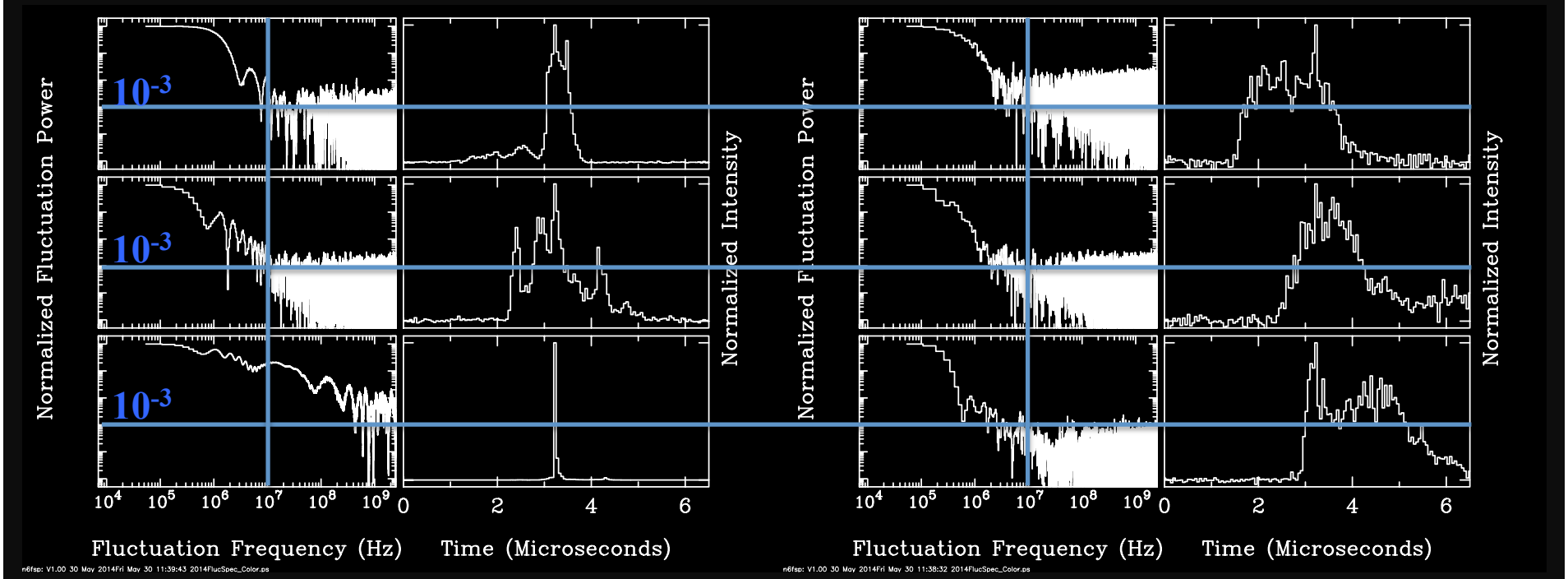
Adjust Dispersion Measure



Modulation Spectra

Main Pulses

Interpulses



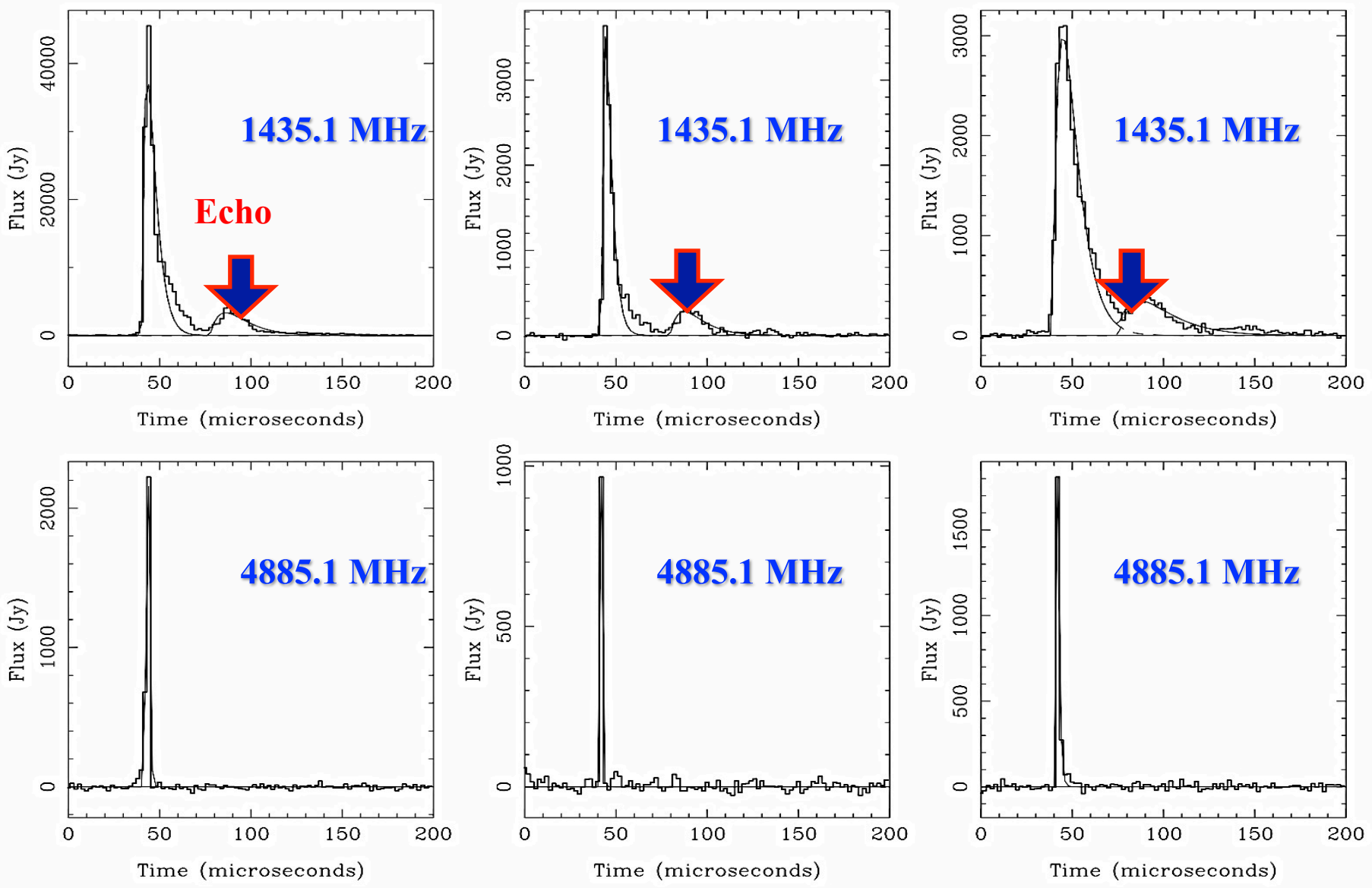
Unexpected Discoveries

Giant Pulse Echoes

Dynamic Spectra:
Interpulse Bands

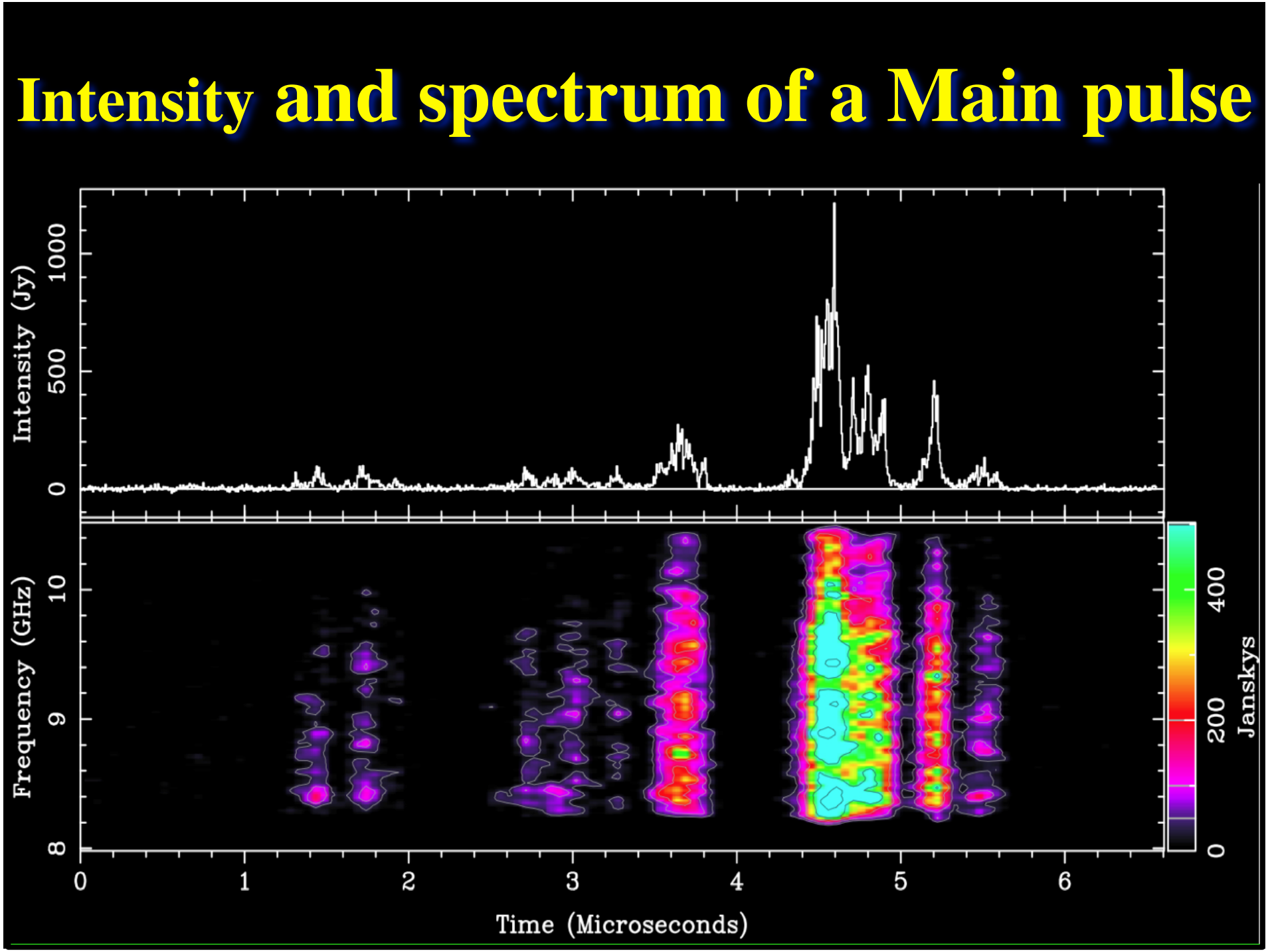
Main pulse DM ≠ Interpulse DM

Giant pulse Echoes

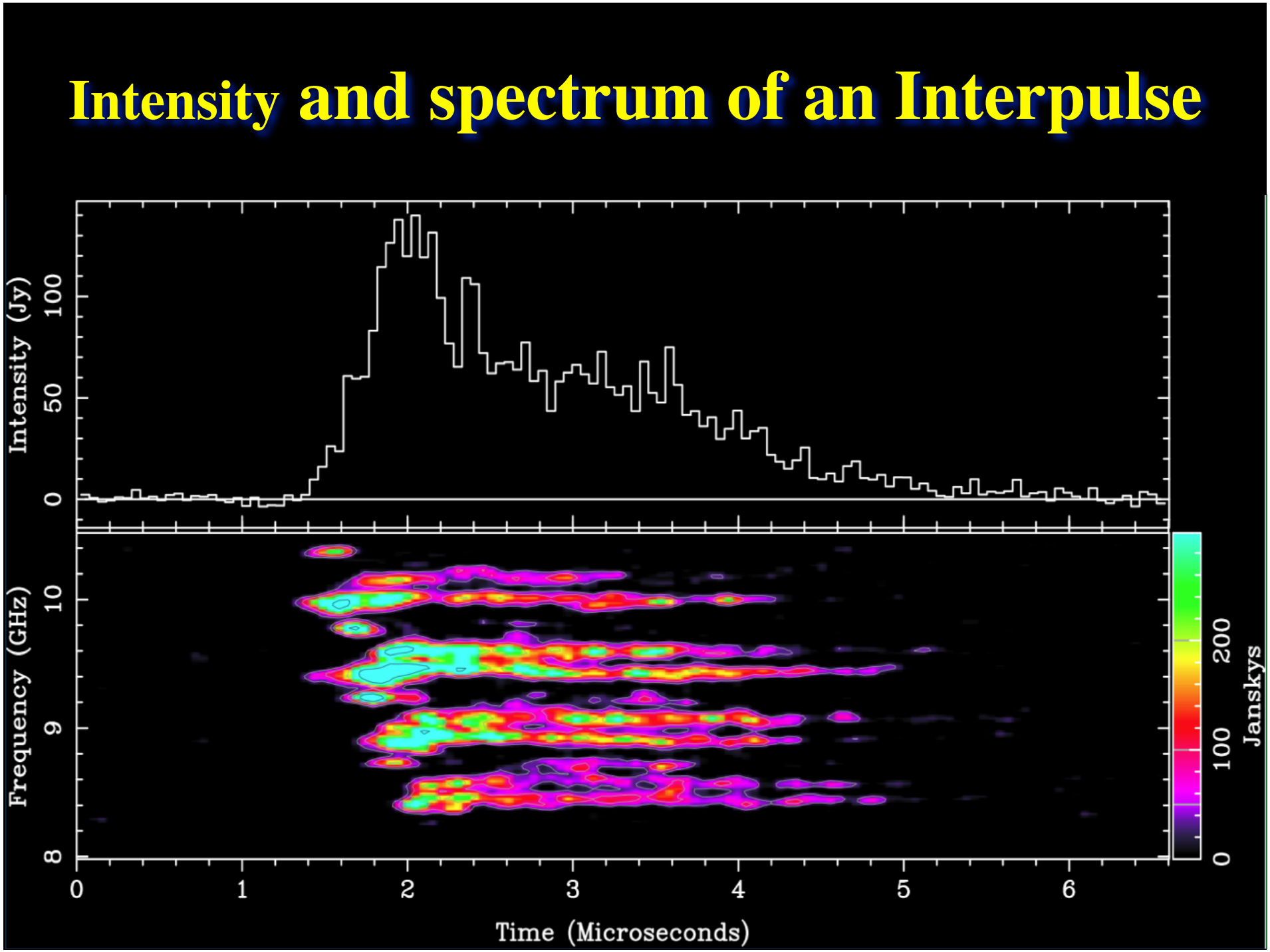


Dynamic Spectra

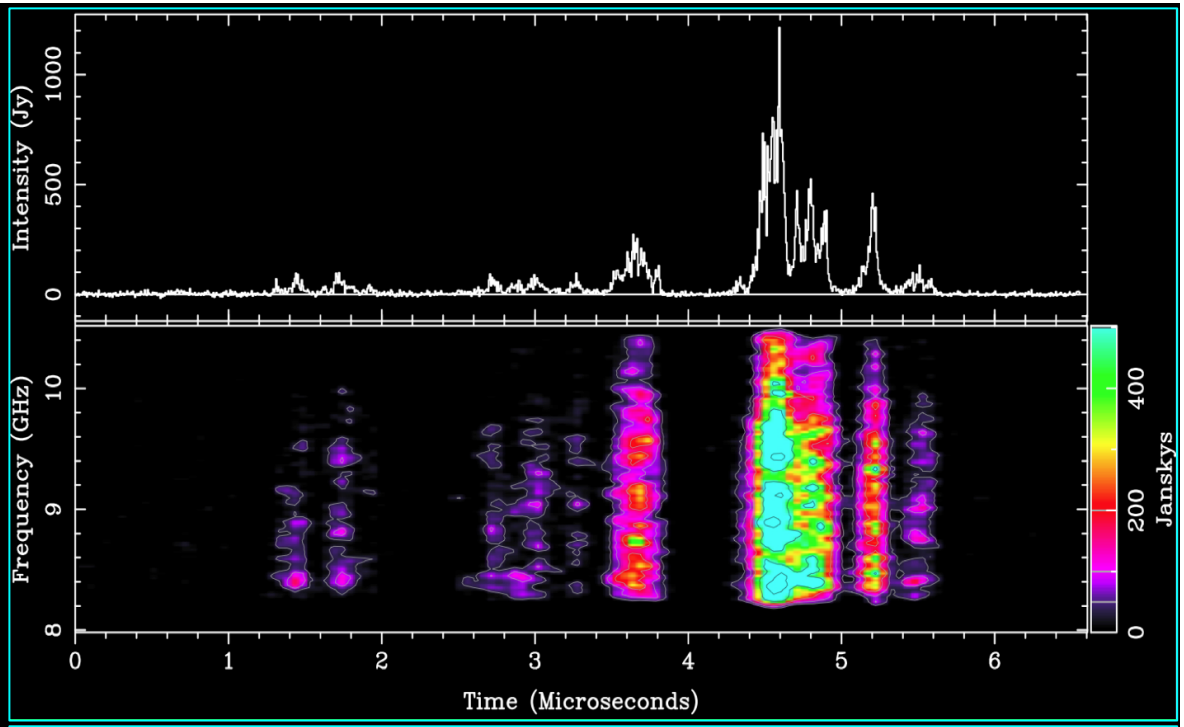
Intensity and spectrum of a Main pulse



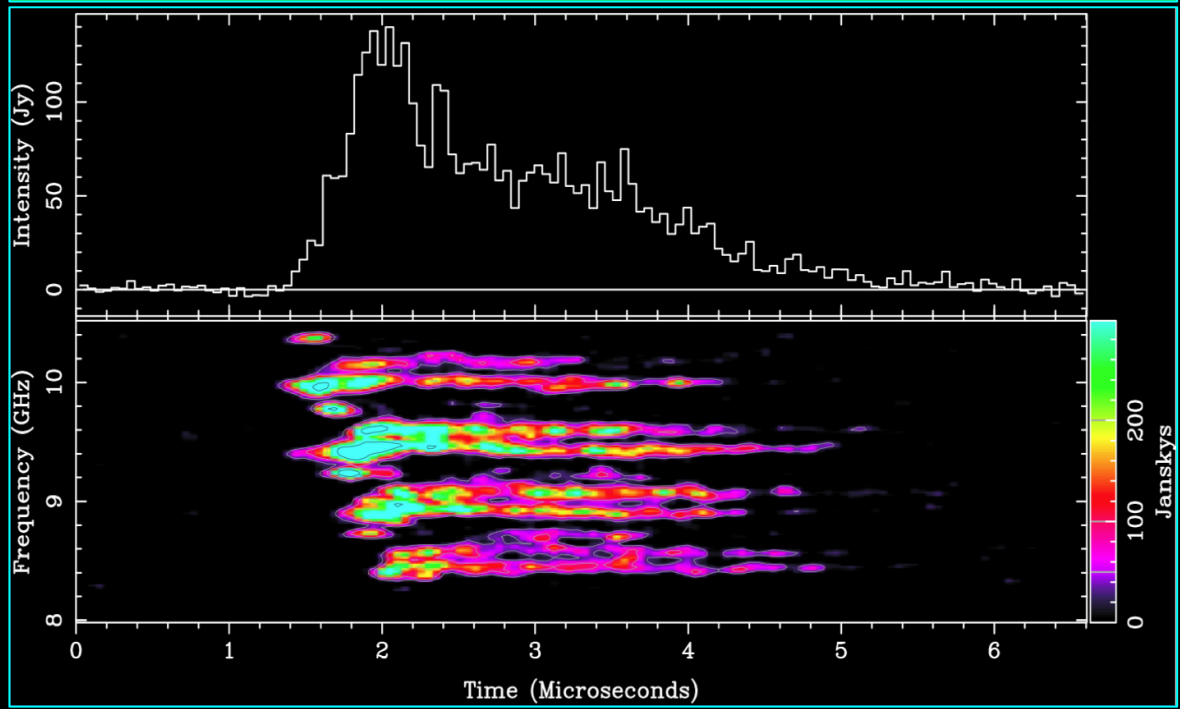
Intensity and spectrum of an Interpulse



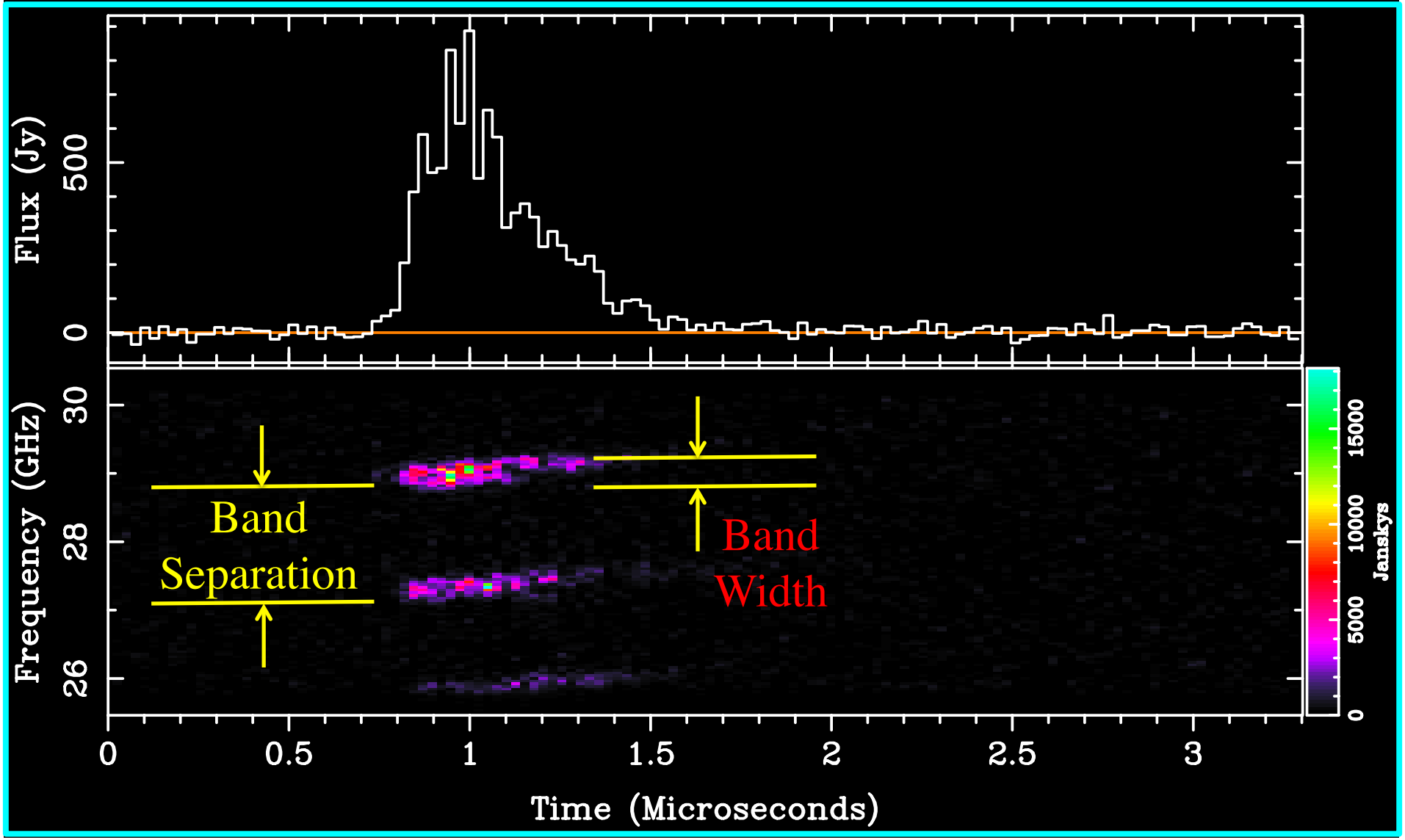
Main pulse:
Wideband



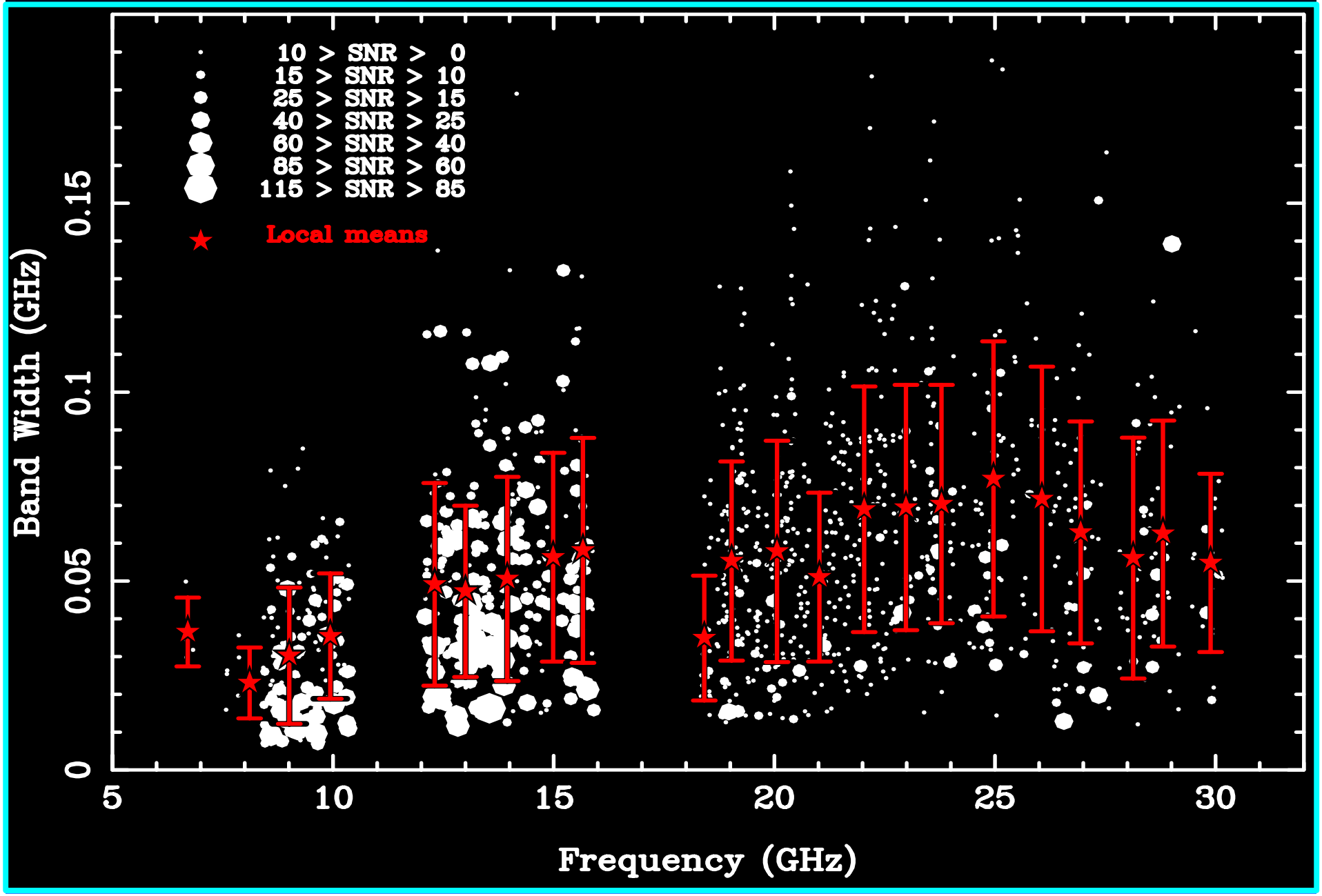
Interpulse:
Banded



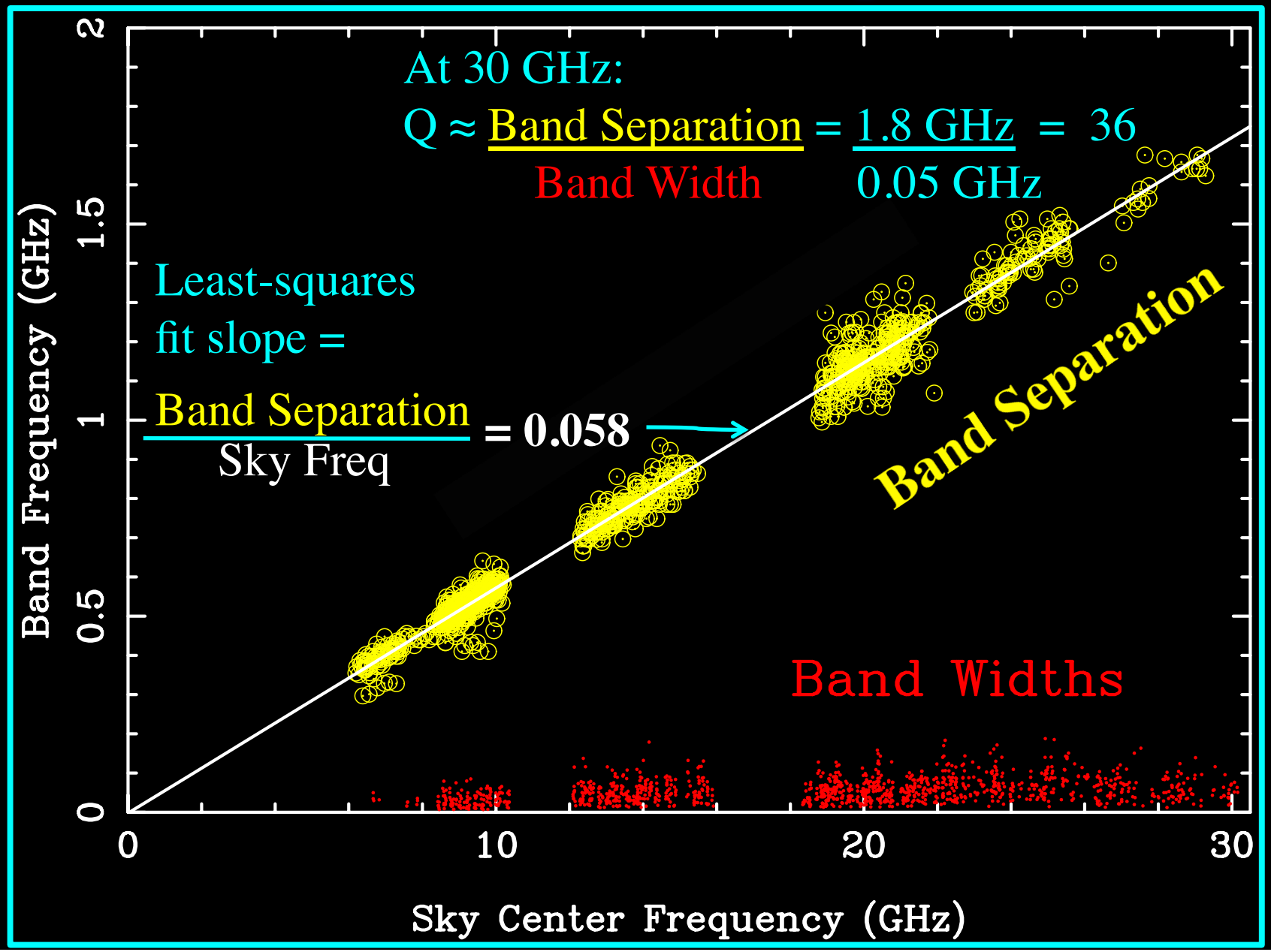
Some definitions:



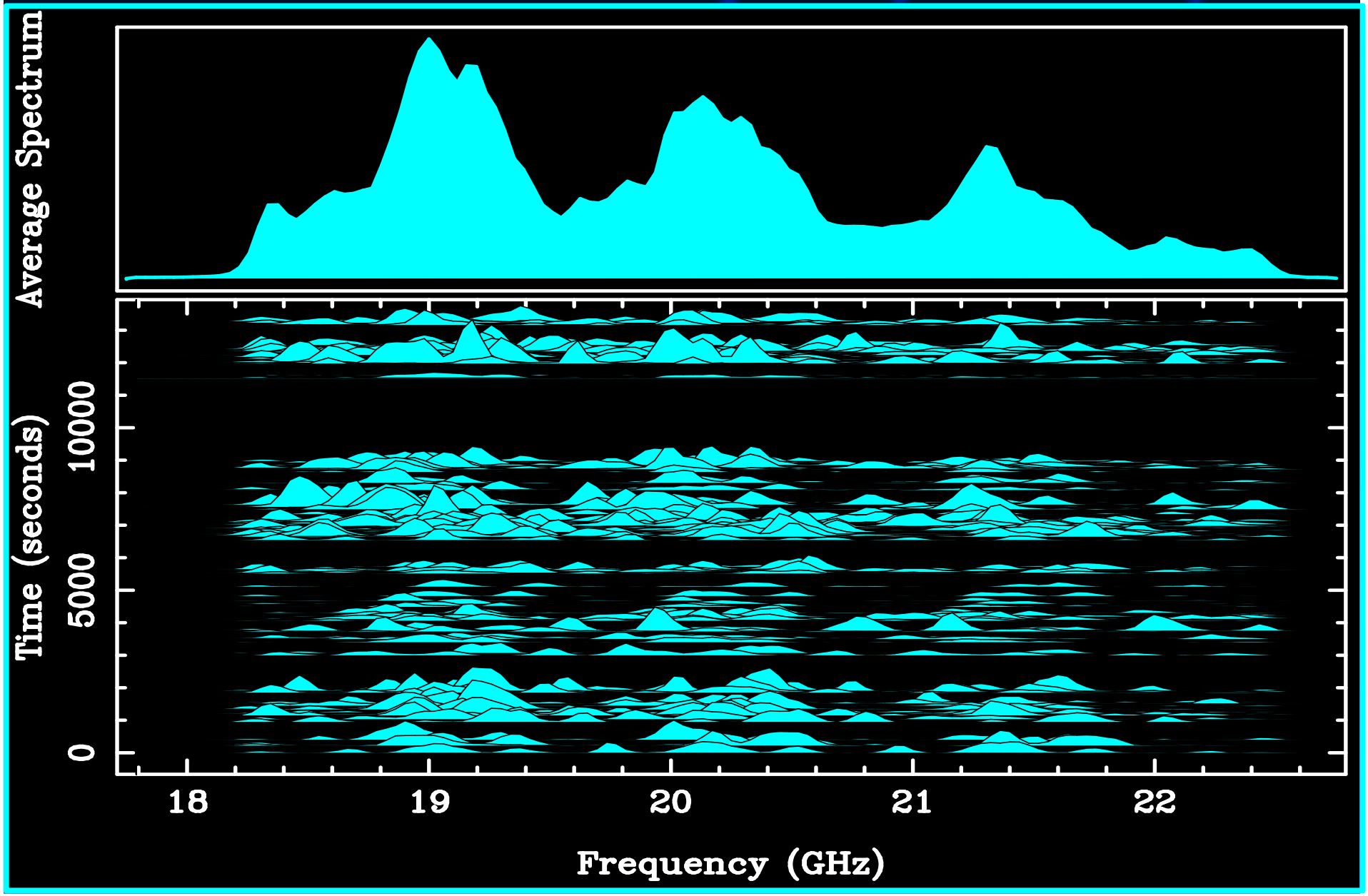
Interpulse band bandwidths



Interpulse Band Frequencies

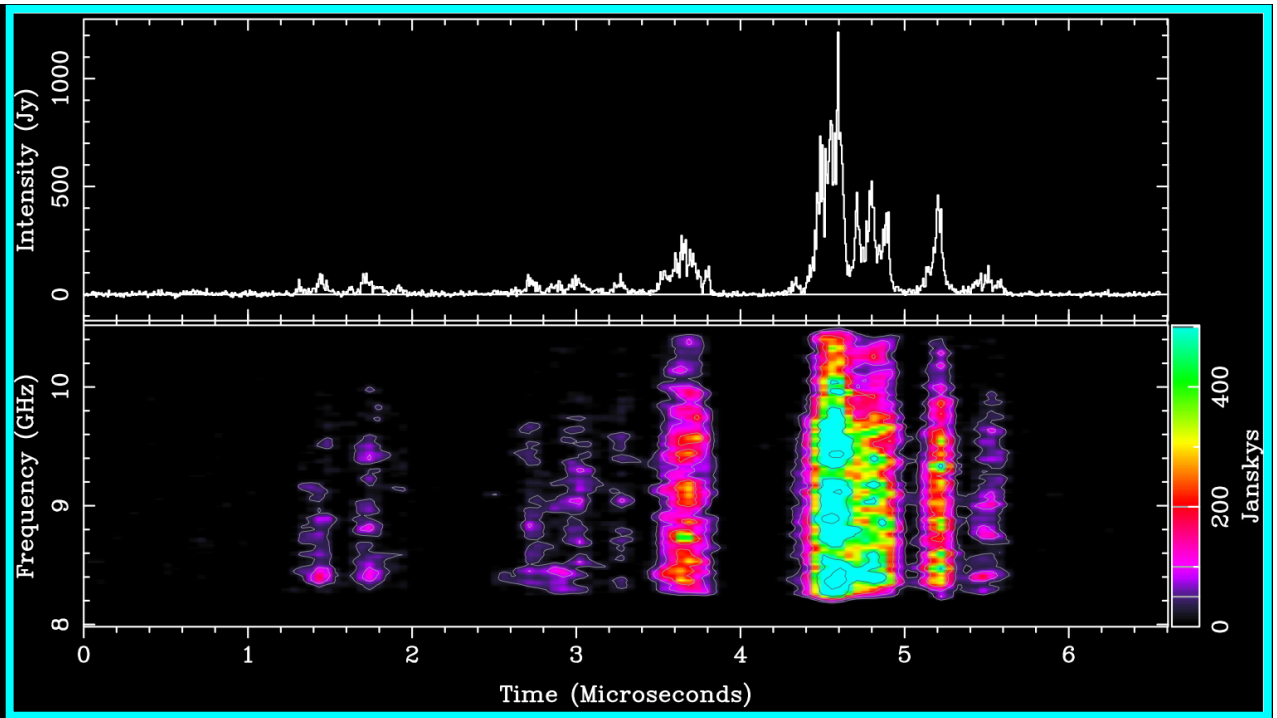


Band Center Frequency Memory

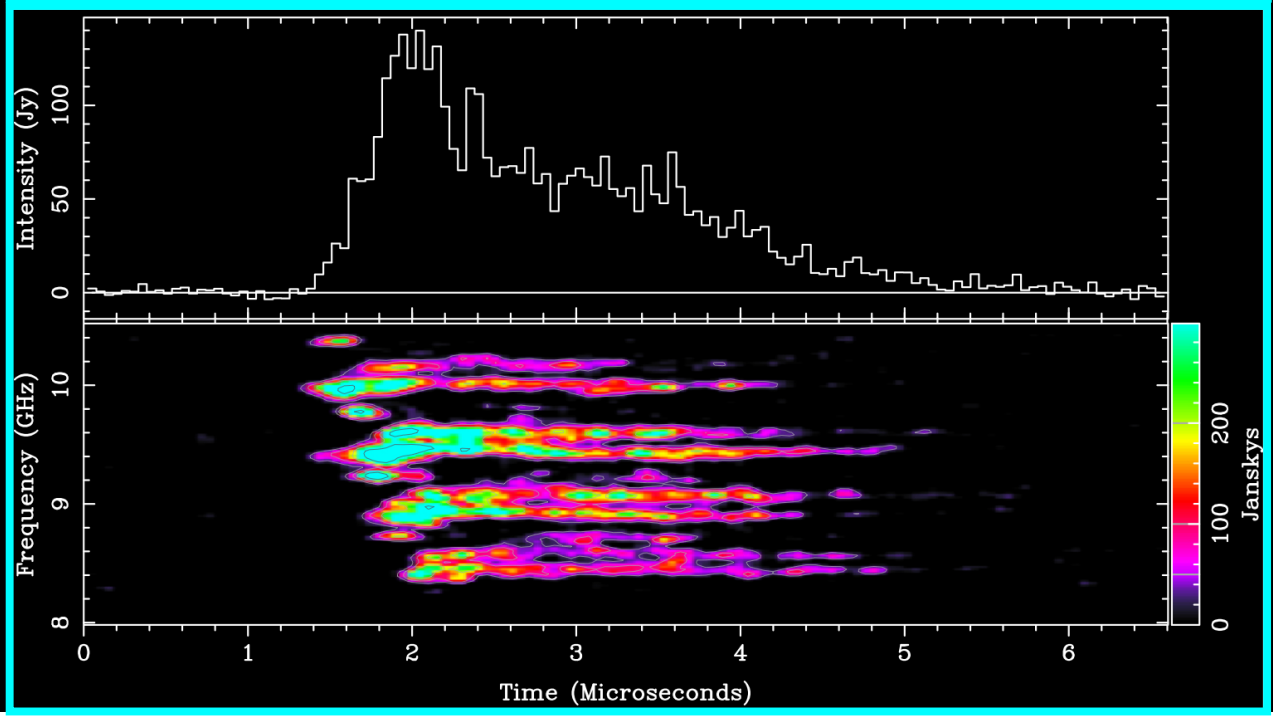


Main pulse/ Interpulse Dispersion

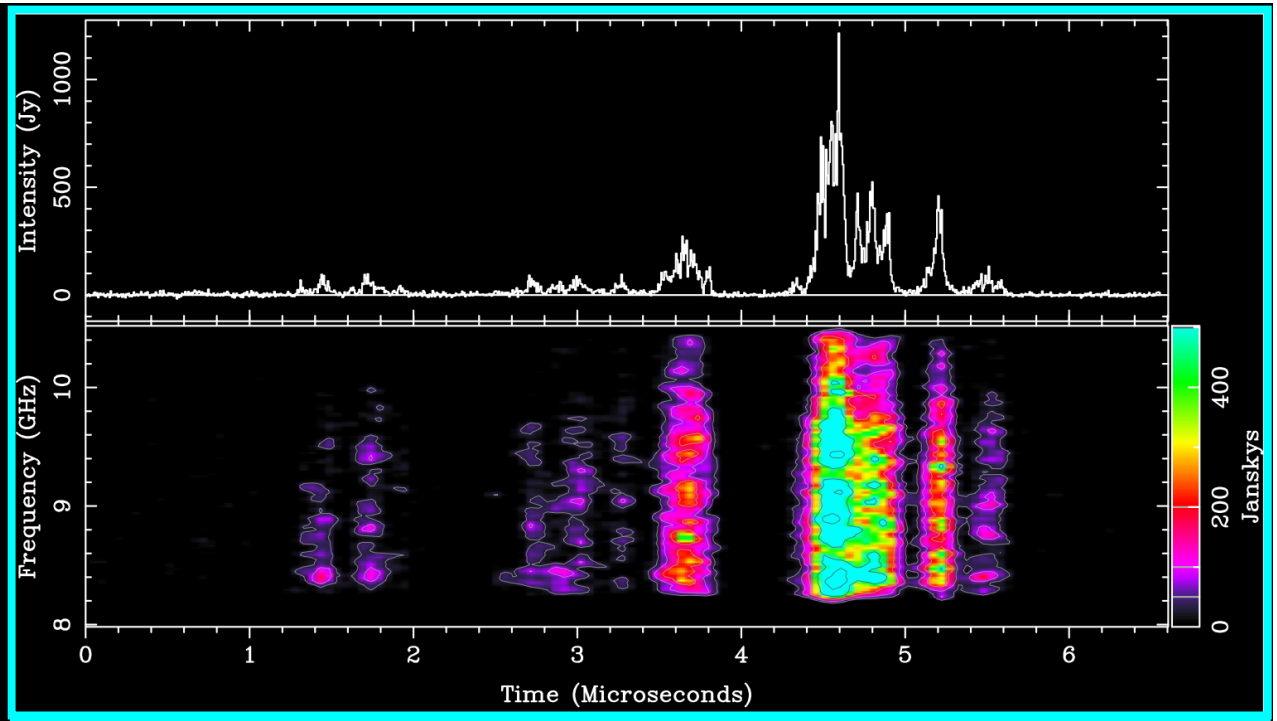
Main pulse



Interpulse

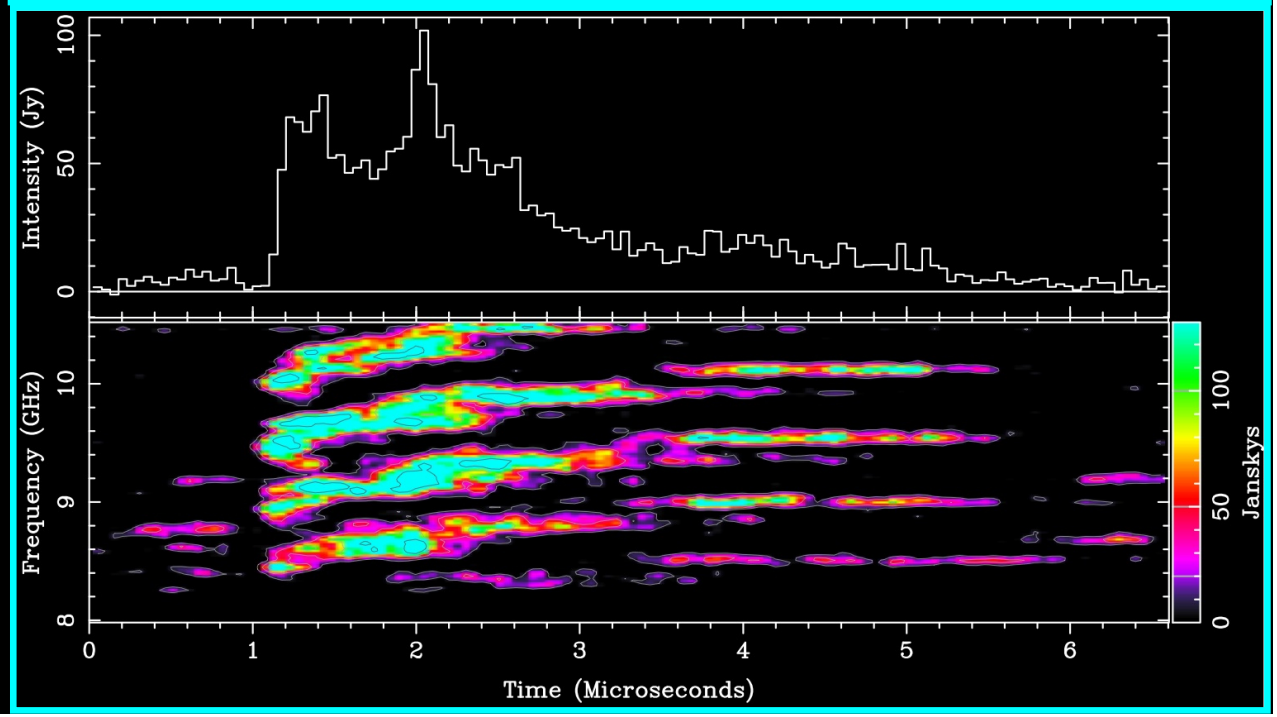


Main Pulse

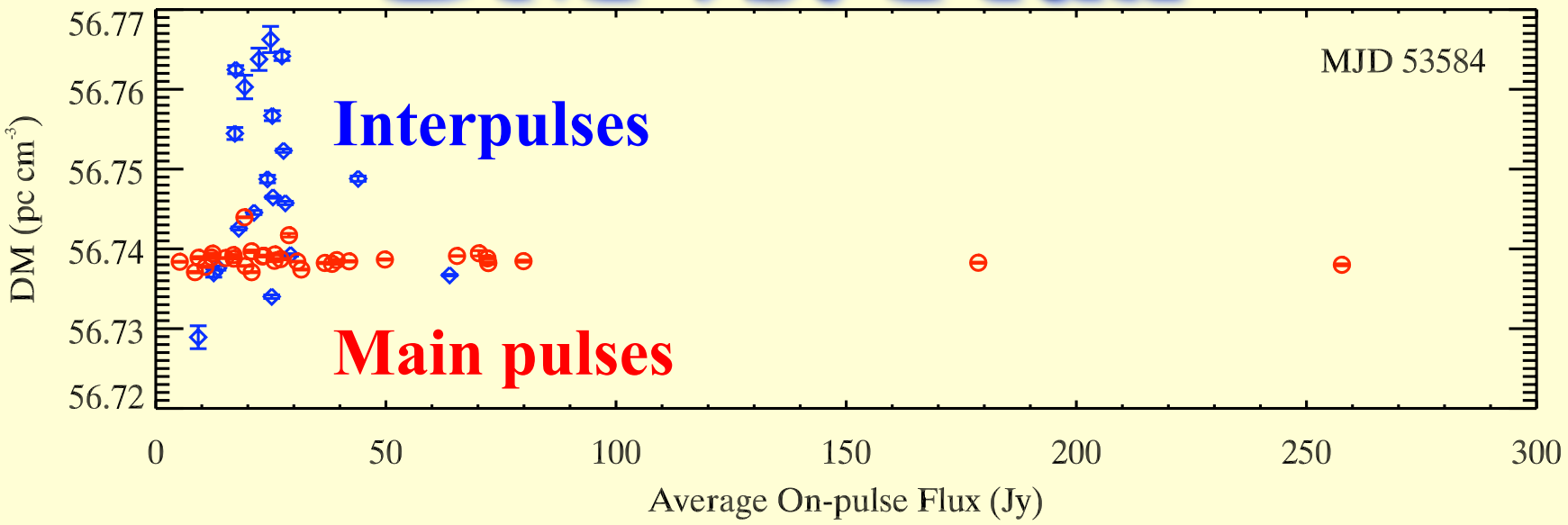


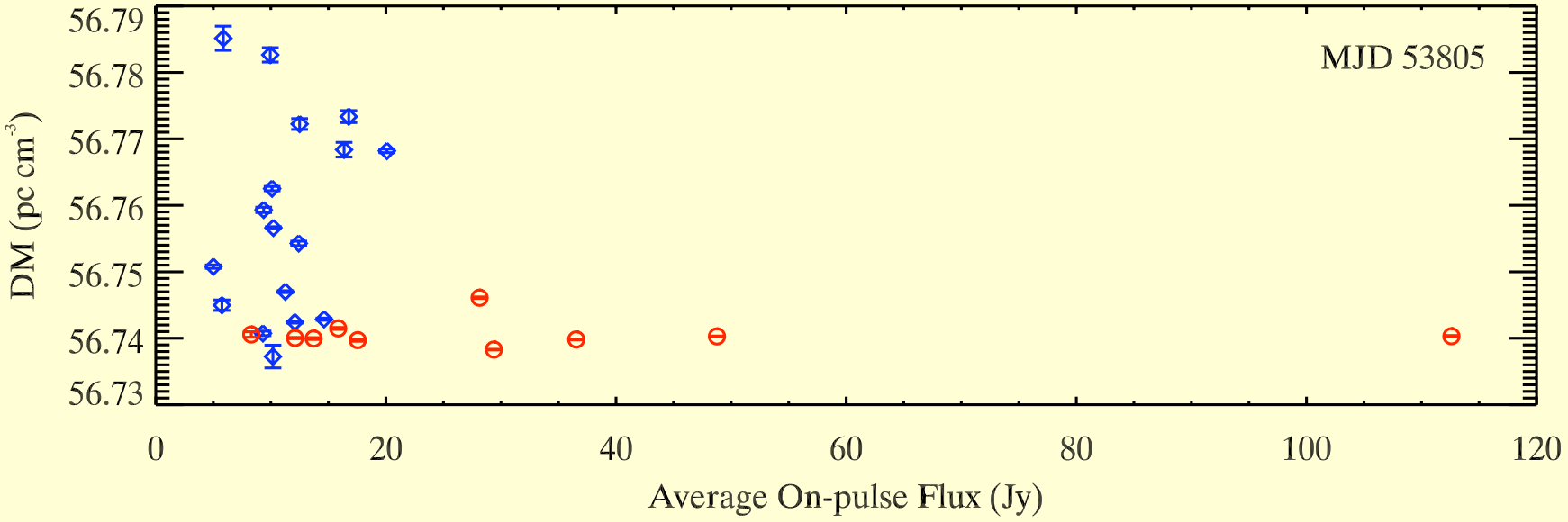
Interpulse

Dispersion corrected

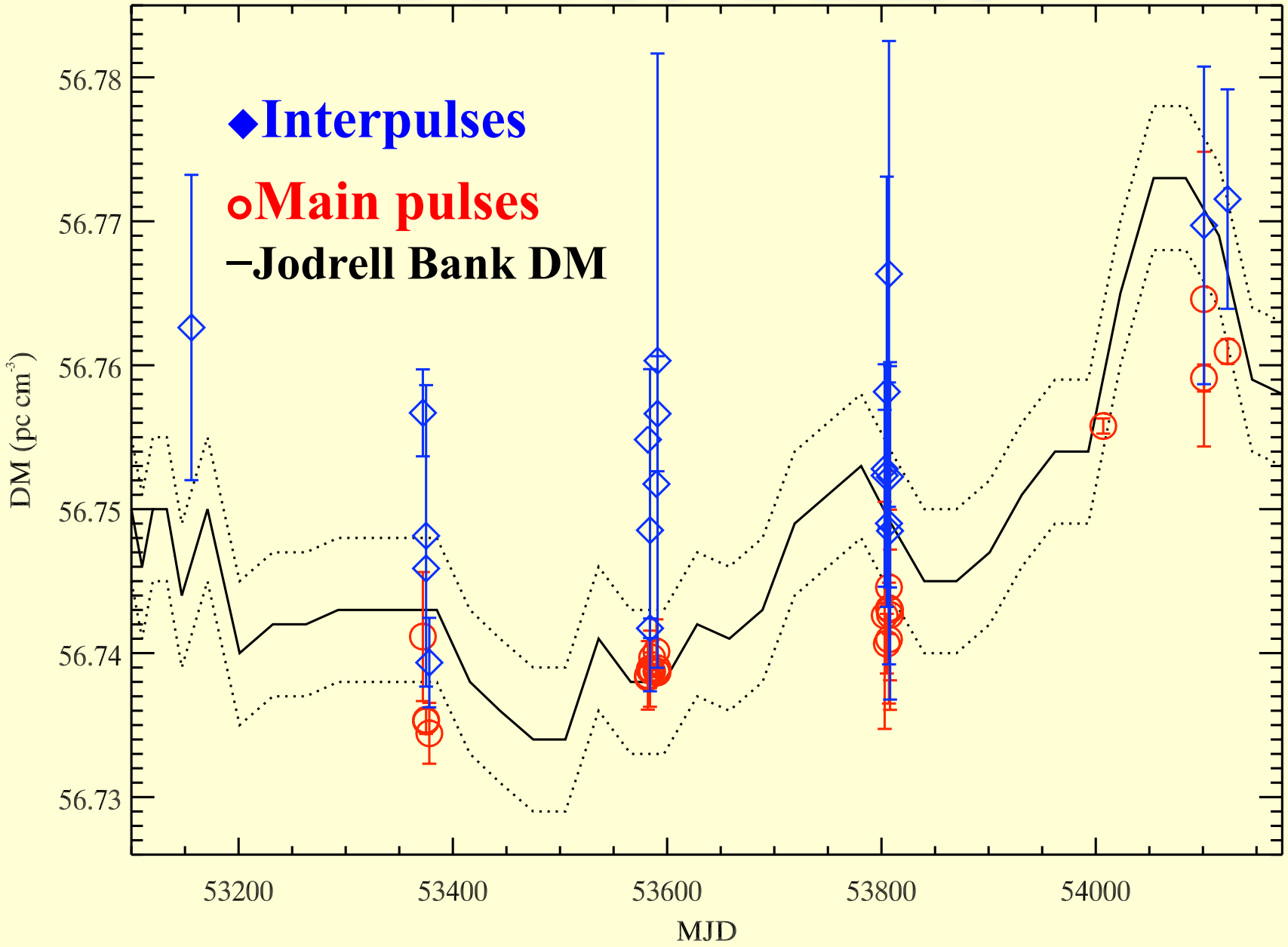


DM *vs.* Flux


MJD 53584
Interpulses
Main pulses
DM (pc cm^{-3})
56.77
56.76
56.75
56.74
56.73
56.72
0
50
100
150
200
250
300
Average On-pulse Flux (Jy)


MJD 53805
DM (pc cm^{-3})
56.79
56.78
56.77
56.76
56.75
56.74
56.73
0
20
40
60
80
100
120
Average On-pulse Flux (Jy)

DM *vs.* Time


◆Interpulses
○Main pulses
–Jodrell Bank DM
DM (pc cm^{-3})
56.78
56.77
56.76
56.75
56.74
56.73
53200
53400
53600
53800
54000
MJD

Summary

Fast sampling: versatility in processing allows detailed emission studies.

"The more you look, the more you see."

The Crab pulsar: Continues to "amaze and mystify"

Future

Dedispersion Processing:

My old, 8-core Mac:

5 GHz data bandwidth: 4000x real time.

(2 ms data in 8 seconds)

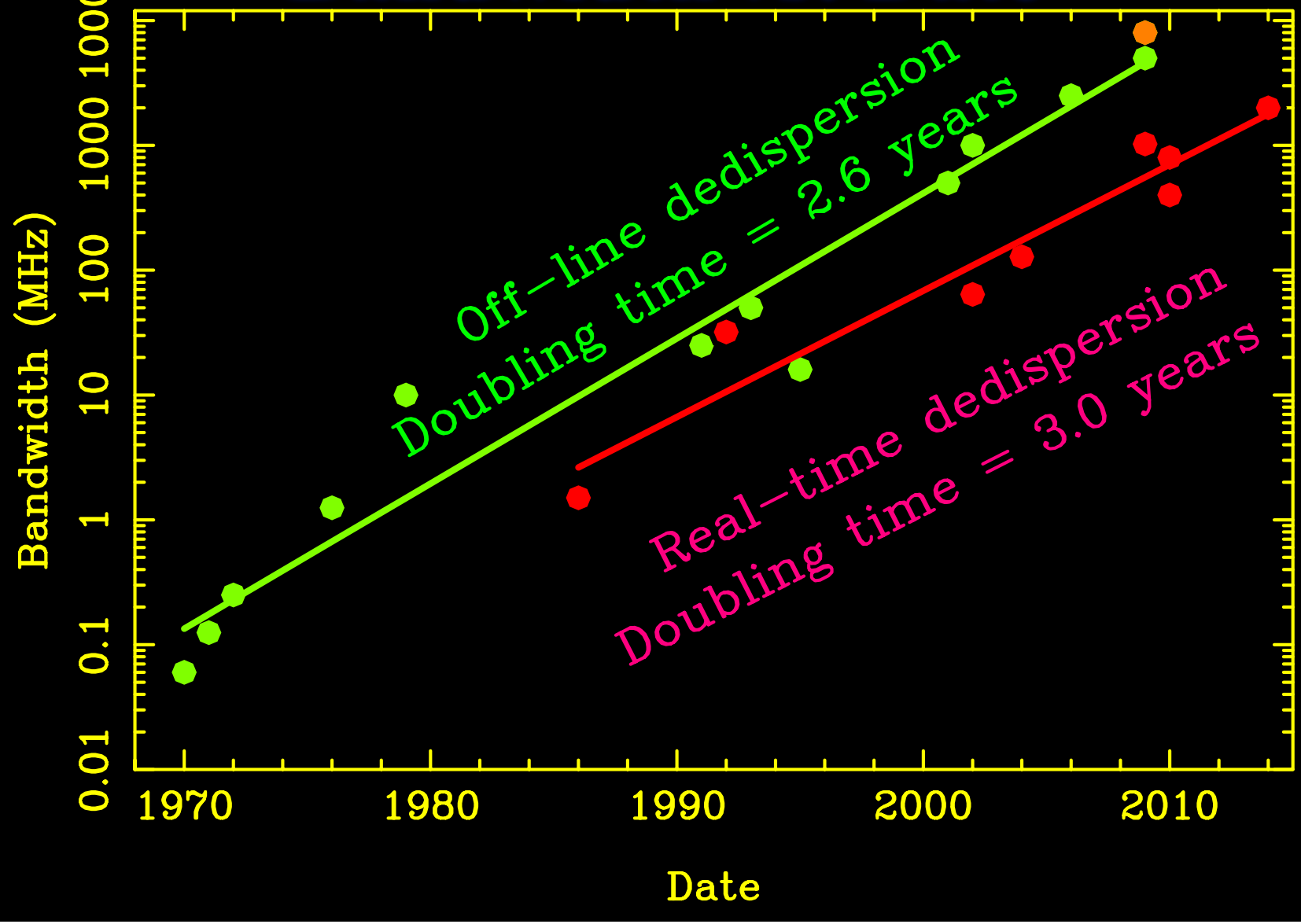
[with lots of diagnostic overhead]

Add *n* GPUs (Graphics Processor Units):

Processing time reasonable.

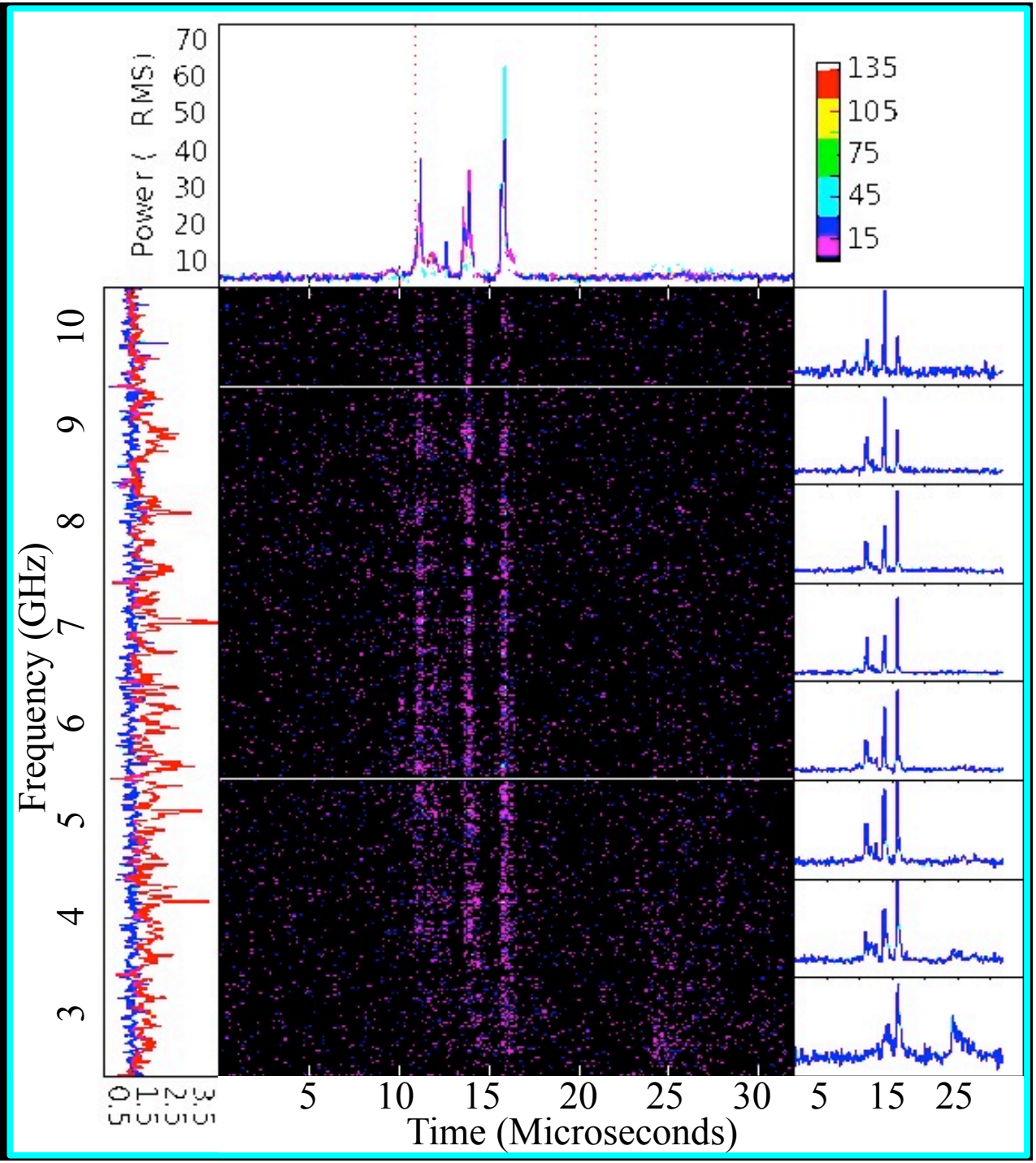
Moore's Law:

Coherent Dedispersion History: Bandwidth *vs.* Date



Giant Main Pulses are Wideband

From Glenn Jones at the GAVRT Telescope



The End