The LWA and Pulsar Timing Arrays

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31-July 2020 LWA Users Meeting, Zoom, NM

The NANOGrav Physics Frontiers Center

NANOGrav
Physics Frontiers Center

We have grown to about 120 students and scientists at ~40 institutions:

California Institute of Technology 1891
Cornell University
F&M
Lafayette College
Vanderbilt University
Montana State University
NRAO
McGill
UAH
The University of Alabama in Huntsville
Oberlin College
USRA
PennState 1855
Huazhong University of Science and Technology
W University of Washington Bothell
University of Virginia 1819
UBC
University of Michigan
The University of California Berkeley 1868
Fisk University 1866
The University of Texas Rio Grande Valley
University of Wisconsin Milwaukee
UWM
Notre Dame of Maryland University 1895
CfA Harvard-Smithsonian Center for Astrophysics
Max-Planck-Institut für Radioastronomie
Rochester Institute of Technology R·I·T 1829
Illinois
University of Illinois at Urbana-Champaign
National Time Service Center
Chinese Academy of Sciences
UEA
University of East Anglia
Columbia University
NCSA
Swarthmore
U.S. Naval Research Laboratory
Harvard
University of Maryland 1856
Universitas Budapestinensis de Rolando Eötvös nominata
Manchester 1824
The University of Manchester
Flatiron Institute
Hillsdale College
spherical cow group
MOO

NANOGrav = North American Nanohertz Observatory for Gravitational Waves

NANOGrav

The Green Bank Telescope and the Arecibo Observatory

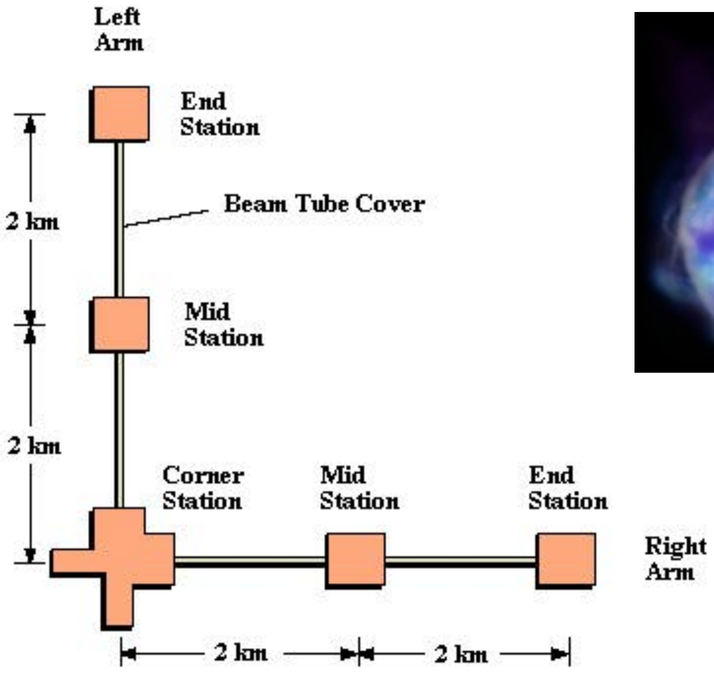
Our measurements are made every 3 weeks (with 7 best pulsars observed weekly), ~30min/pulsar on 78 millisecond pulsars, with the two most sensitive radio telescopes in the world:

Arecibo Observatory (AO), PR
World's second
largest single-dish
radio telescope

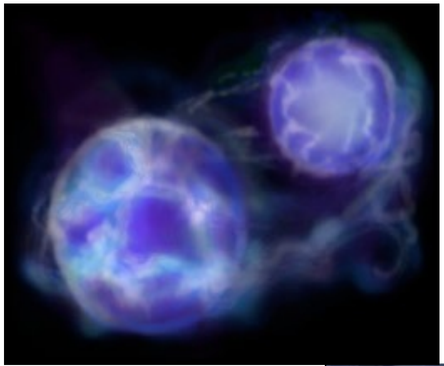
Green Bank Telescope (GBT), WV
World's largest steerable
single-dish radio
telescope

- The Very Large Array is also contributing to our data sets, and MOU with CHIME telescope recently signed
- Moore Foundation has recently funded development of an Ultra-Wideband Receiver for the GBT

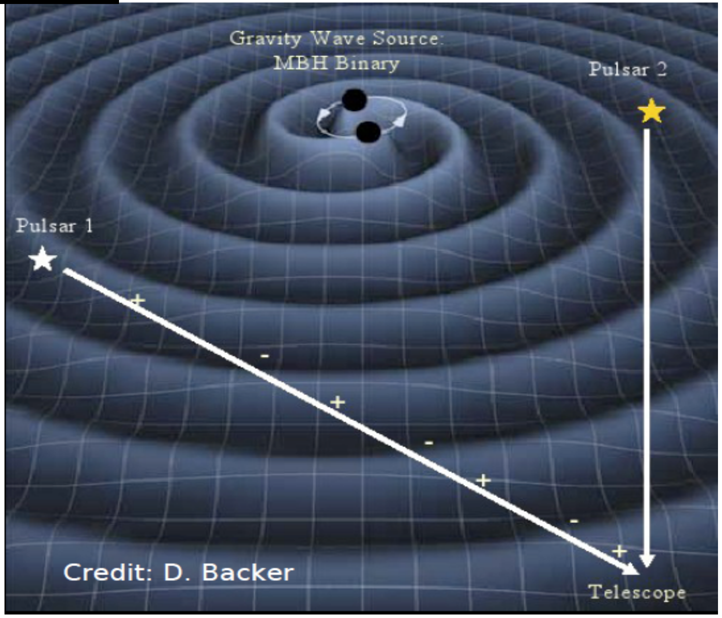
Both LIGO and PTAs probe a ΔL on the scale of their respective “nuclei”



Schematic layout of LIGO Site at Hanford, WA
(Installation at Livingston, LA has no mid-stations)

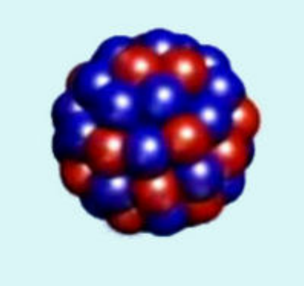


h = strain = $\Delta L/L = 10^{-15}$
PTA $\Delta L \sim 3$ km

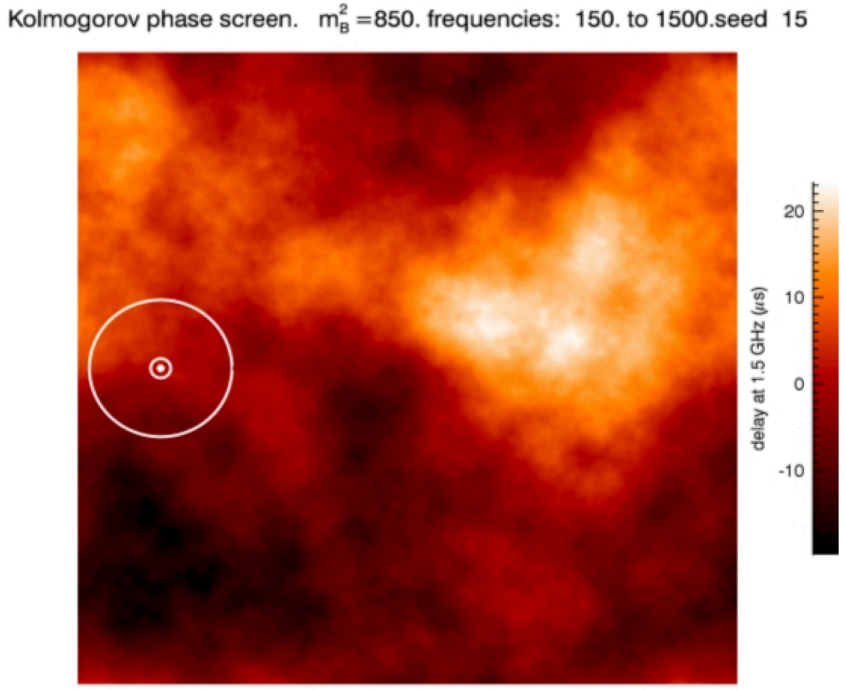


Credit: D. Backer

h = strain = $\Delta L/L = 10^{-21}$
LIGO $\Delta L \sim 10^{-19}$ m



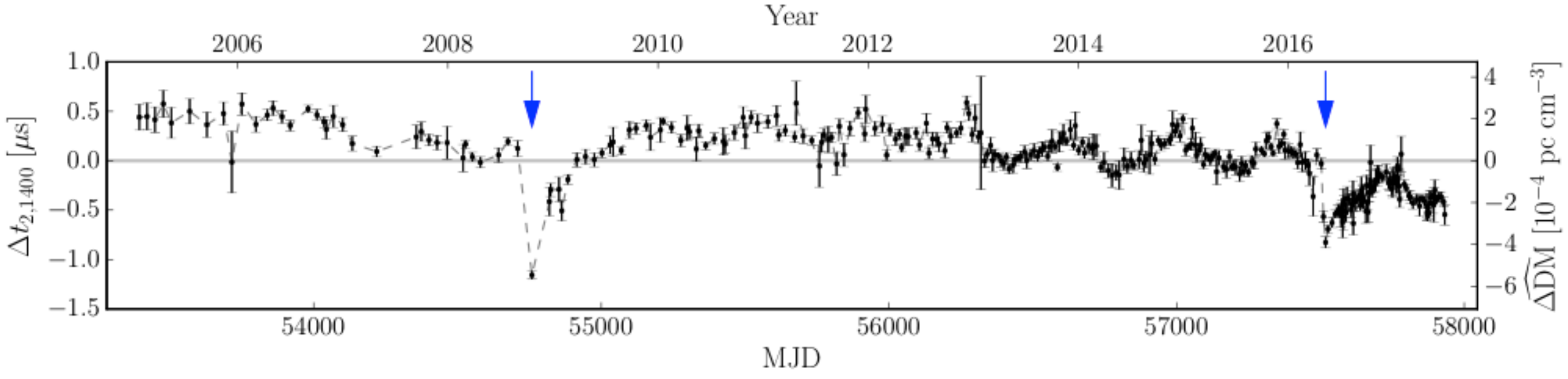
NANOGrav and the LWA: Mitigating Pulsar Scattering for GW Detection



From Cordes, Shannon, Stinebring (2016)

- In future, wide-bandwidth receivers, we may need to account for frequency-dependent dispersion measures (left)
- 6 NANOGrav pulsars currently detectable w/LWA (of 76, but 3 are in 13 most GW sensitive); more possible in future with cyclic spectroscopy
- as in Bansal et al. (2019) - want to understand scattering timescale vs. frequency for all NANOGrav pulsars as widely as possible

- Resolved pulsar scattering screens can also model or limit unusual scattering events along line-of-sight; example J1713+0747



from Lam et al. (2018)

Current LWA Observing Program (LD014)

- Searching for four NANOGrav pulsars with the LWA that haven’t yet been detected (below)
- Some hints of a detection in several, but still processing data
- If any one of them detected, will be in a position to monitor a future ISM event like the J1713+0747 event reported in Lam et al. (2018)
- Will also search for pulsations in an unidentified steep spectrum point source
- Thanks to Alex Dulemba (Hillsdale student), Froney Crawford (Franklin and Marshall), Don Fasce (F&M)

Table 1. Target Pulsars and a Candidate Pulsar

Pulsar Name / Candidate Coords	τ_{scatt}[a] (ns)	S1400 (mJy)
J1012+5307 (5hr)	2.5	3.2
J1640+2224 (5hr)	2.7	0.7
J1713+0747 (5hr)	7.1	8.5
J1909–3744 (5hr)	4.9	1.6
06:36:43 +18:37:58.9 (1hr)	N/A	110 (74 MHz; not pulsed)

[a] from Levin et al. (2016)

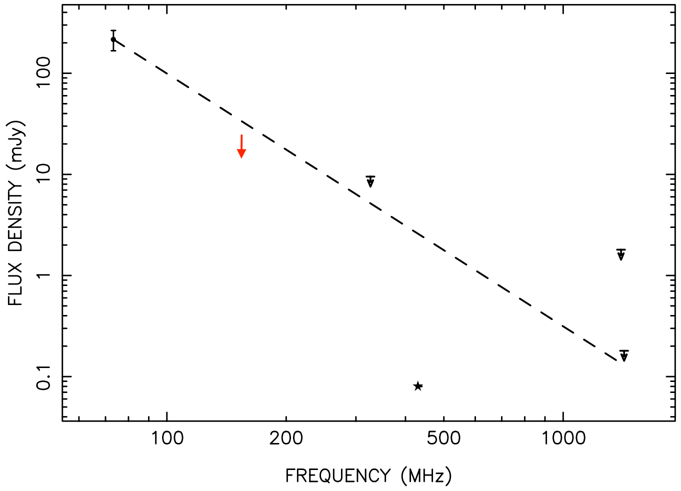
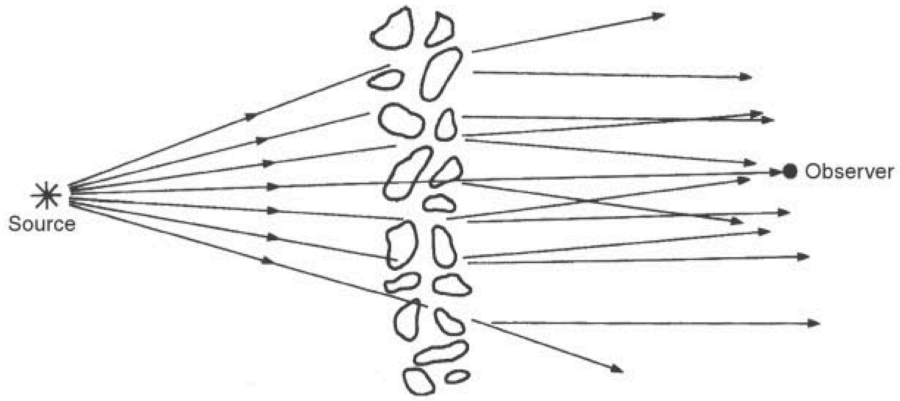


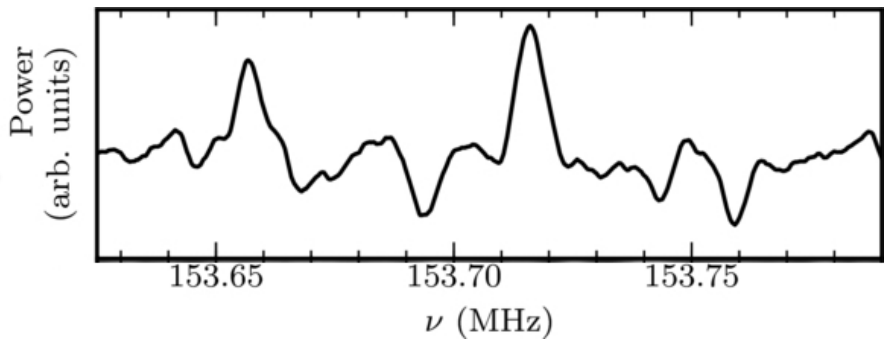
Figure 2. 74 MHz detection of an unassociated steep-spectrum point source VLA J0636+1838. Black upper limits are from higher VLA frequencies. Red upper limit is from the TGSS survey with the GMRT.

A Brief History of Cyclic Spectroscopy (CS)

- Antoni (2006) [Mechanical Engineering publication]
  - Theoretical foundations
- Demorest (2011)
  - Demonstrated successful deconvolution of ISM's pulse-broadening function on B1937+21 with Arecibo baseband data @430MHz
- Walker, Demorest, van Straten (2013) [WDvS13]
  - Expands Demorest (2011) analysis to derive "delay Doppler image"; e.g. CS version of secondary spectrum
- Archibald, Hessels, Stinebring (2014)
  - Used CS on LOFAR data to improve standard frequency resolution and resolve scintles in dynamic spectra
- Dolch, Lam, et al. (2014) – 1713 Global
  - Used CycSpec backend developed by Glenn Jones in parallel with GUPPI backend; writes cyclic spectra rather than baseband as a data product
- Palliyaguru, Stinebring, McLaughlin, Demorest, Jones (2015)
  - Simulations show that ISM deconvolution via CS can lead to improved timing residuals

Inhomogenous ISM scatters and scintillates pulsar signals.

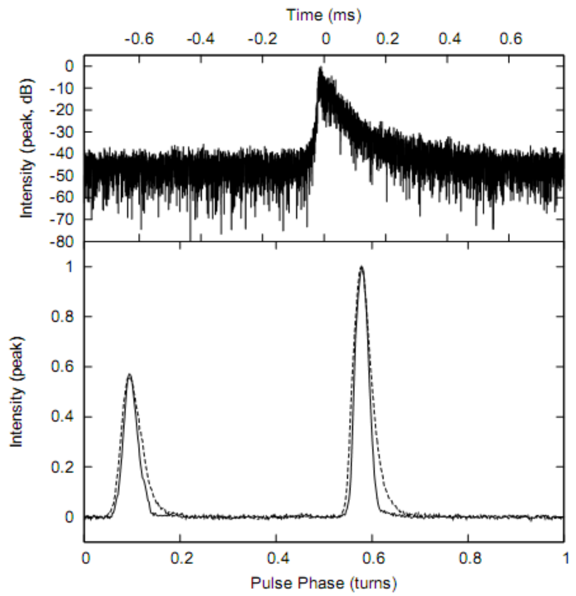




Archibald Hessels & Stinebring (2014)

Cyclic Spectroscopy…

- a signal processing technique useful for pulsed noise
- separates out the intrinsic pulsar signal from the effects of the interstellar medium (Walker, Demorest, Van Straten 2013; Palliyaguru 2015)
- E-field amplitude phase information required. Can be saved as cyclic spectrum to avoid bulky baseband data.

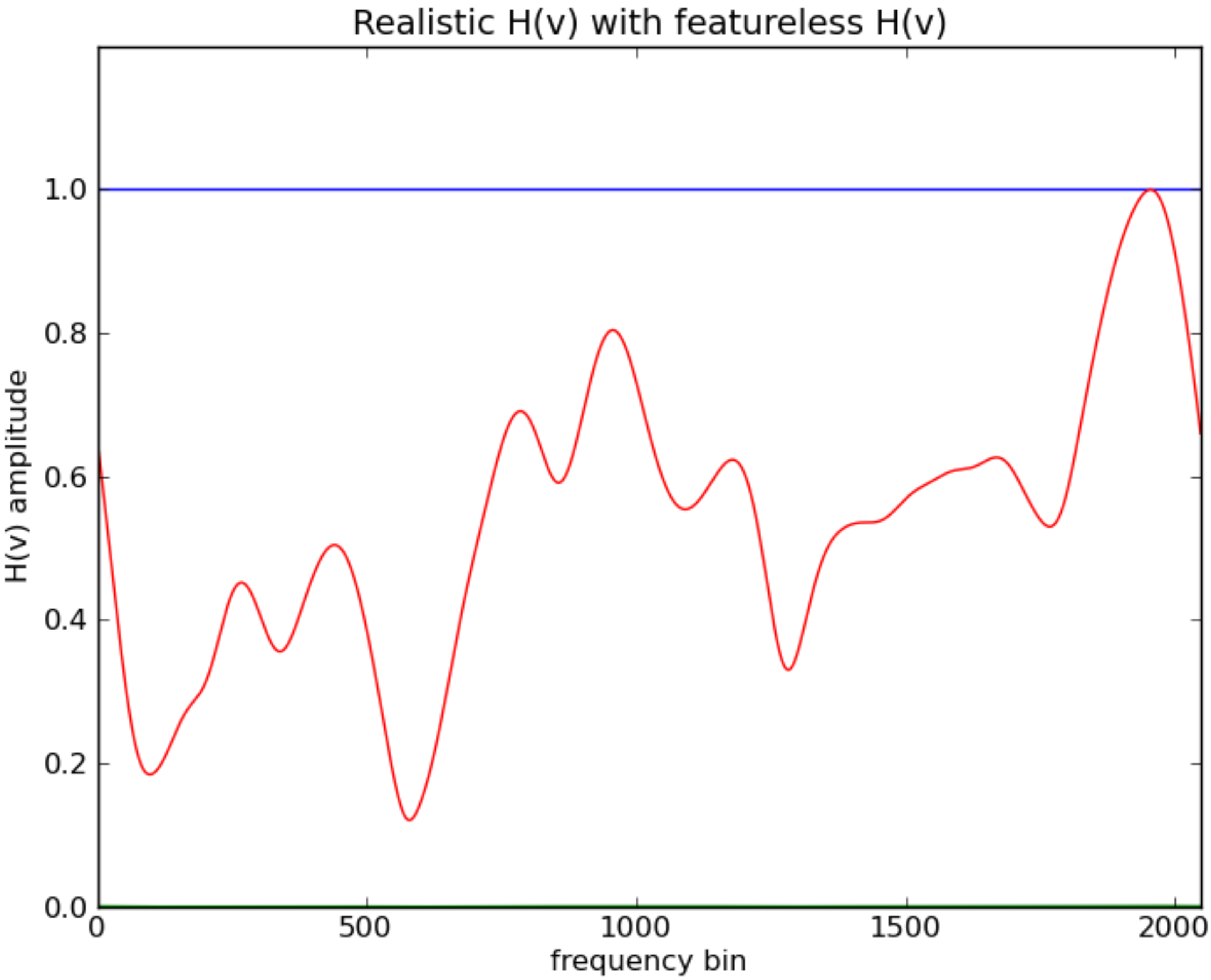


Demorest (2011)

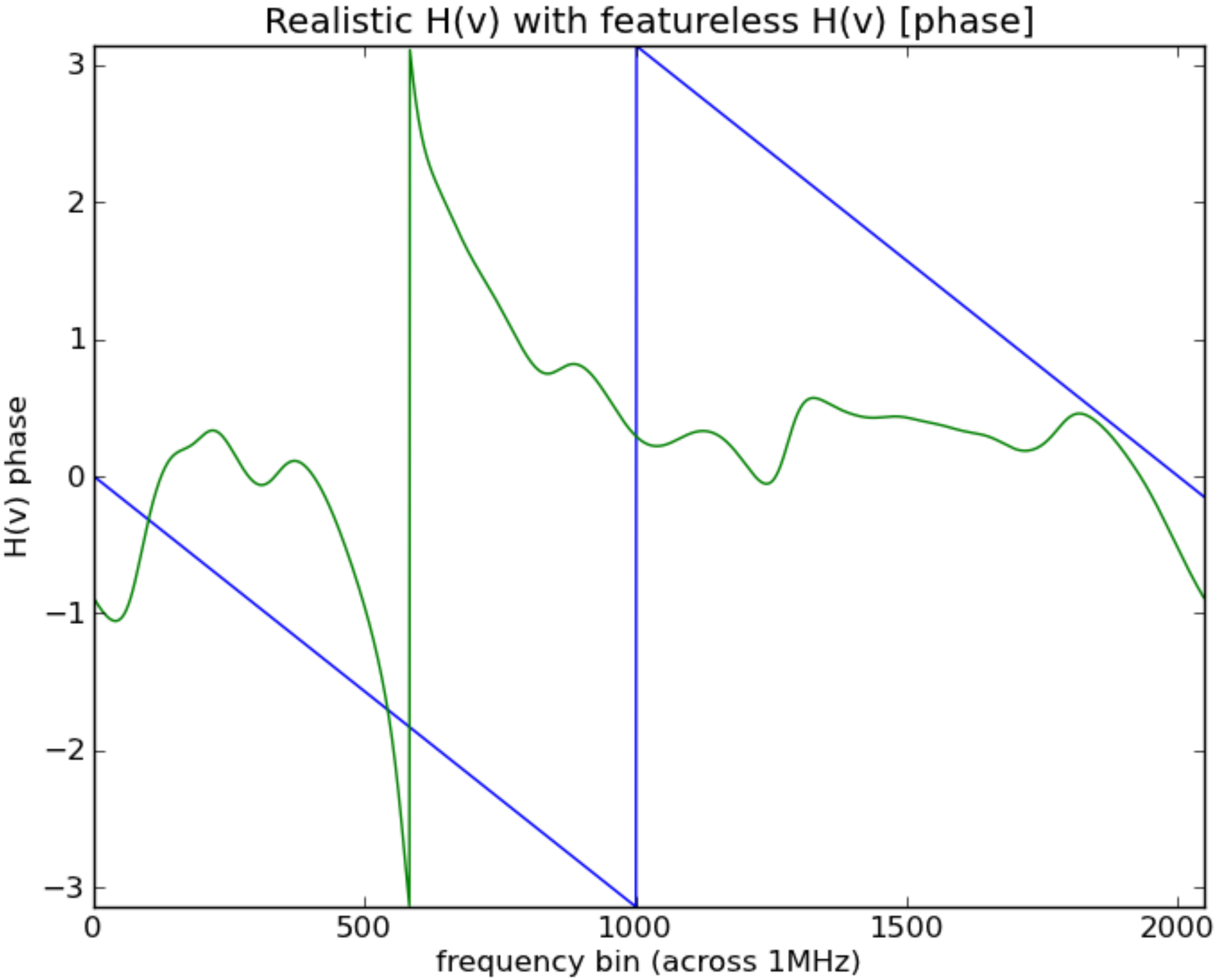
h(t) is best-fit IRF (impulse response function) from ISM

CS aims to deconvolve the ISM's IRF from original pulse profile

H(v) amplitude of example ISM realization



H(v) phase of example ISM realization

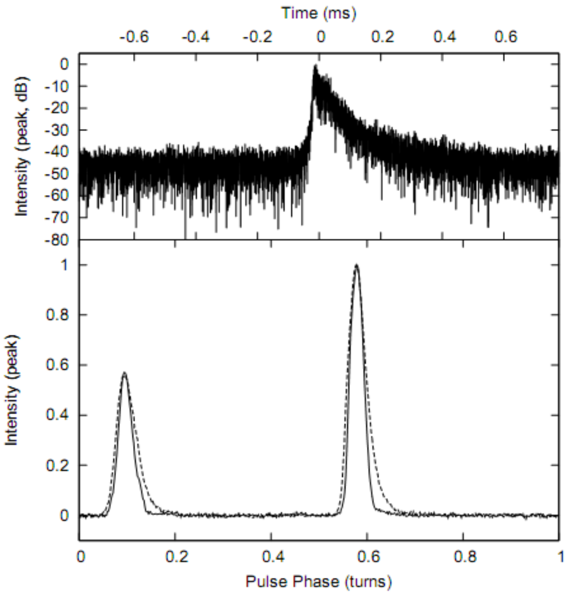


What is a cyclic spectrum?

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

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

real-time CS backend taking cyclic spectra under development at the GBT



h(t) is best-fit IRF (impulse response function) from ISM

CS aims to deconvolve the ISM's IRF from original pulse profile

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

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

From Demorest et al. 2011

$\alpha_n = n/P,$ P = pulse period

How do we determine the transfer function phase (due to interfering E-field phases) from the CS?

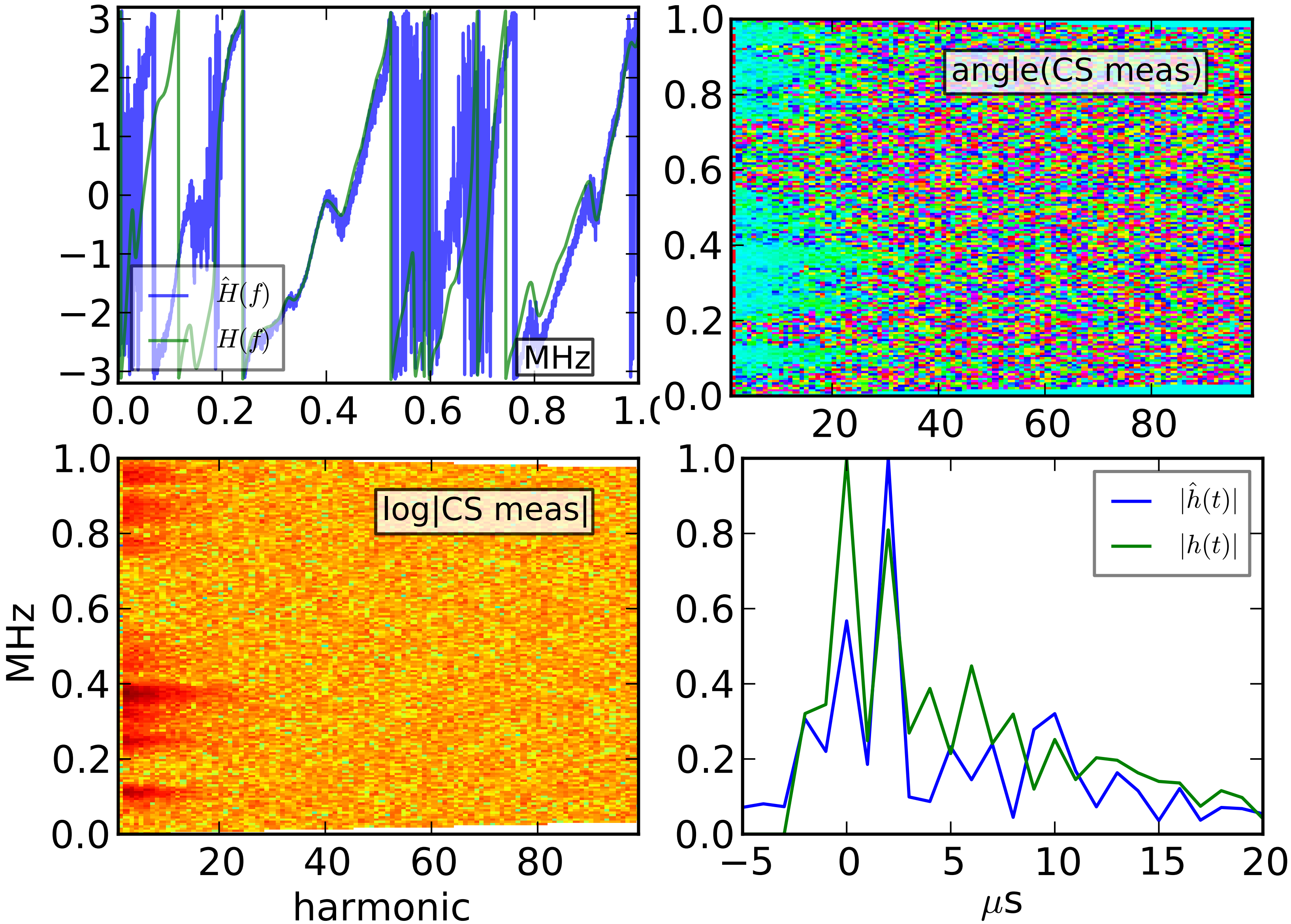
- Best-fit transfer function H comes from Walker, Demorest, van Straten (WDvS) fitting algorithm (WDvS 2013)
- In order to deconvolve the ISM along every ray path, we need E-field phase information: contained in phase of transfer function H of the data we're fitting:

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

$$\begin{aligned}
\phi_S(\nu,\alpha_k) &= \Phi(\nu+\alpha_k/2) - \Phi(\nu-\alpha_k/2) + \phi_{S_0}(\alpha_k) \\
&= \Phi(\nu+\alpha_k/2) - \Phi(\nu-\alpha_k/2) + \phi_{S_0}(\alpha_k) \\
&= \alpha_k \frac{\Phi(\nu+\alpha_k/2) - \Phi(\nu-\alpha_k/2)}{\alpha} + \phi_{S_0}(\alpha_k) \\
&= \alpha_k \frac{\Delta\Phi(H(\nu))}{\Delta\alpha_k} + \phi_{S_0}(\alpha_k) \\
&\approx \alpha_k \frac{\Delta(\Phi(e^{2\pi i\nu\tau}))}{\Delta\alpha_k} + \phi_{S_0}(\alpha_k) \\
&\approx 2\pi\tau\alpha_k + \phi_{S_0}(\alpha_k)
\end{aligned}$$

Punchline: in cyclic spectrum S(ν,α), the average slope of the phase gradient WRT α is the typical scattering time τ

WDvS algorithm on simulated data: 5μs scattering



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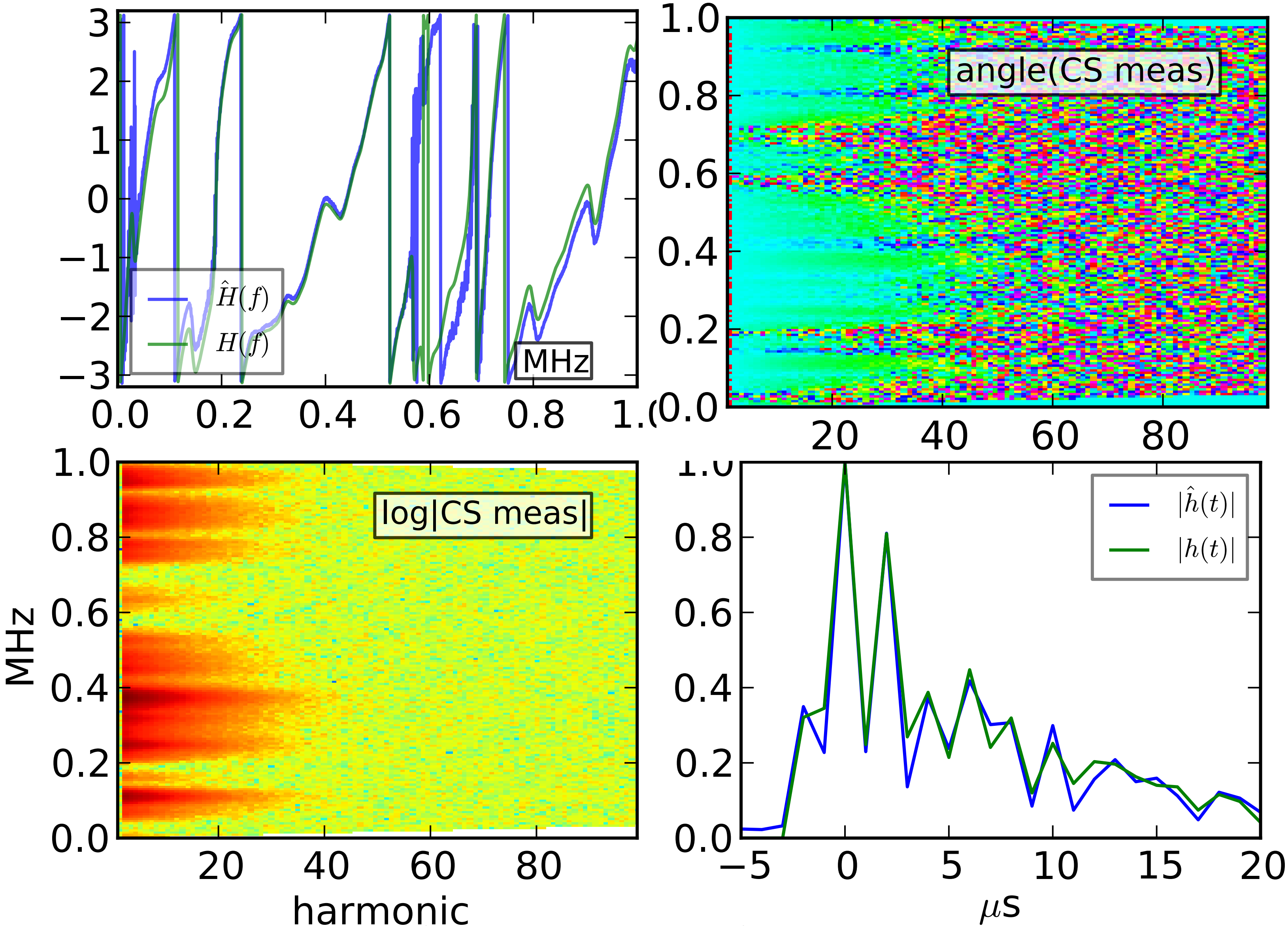
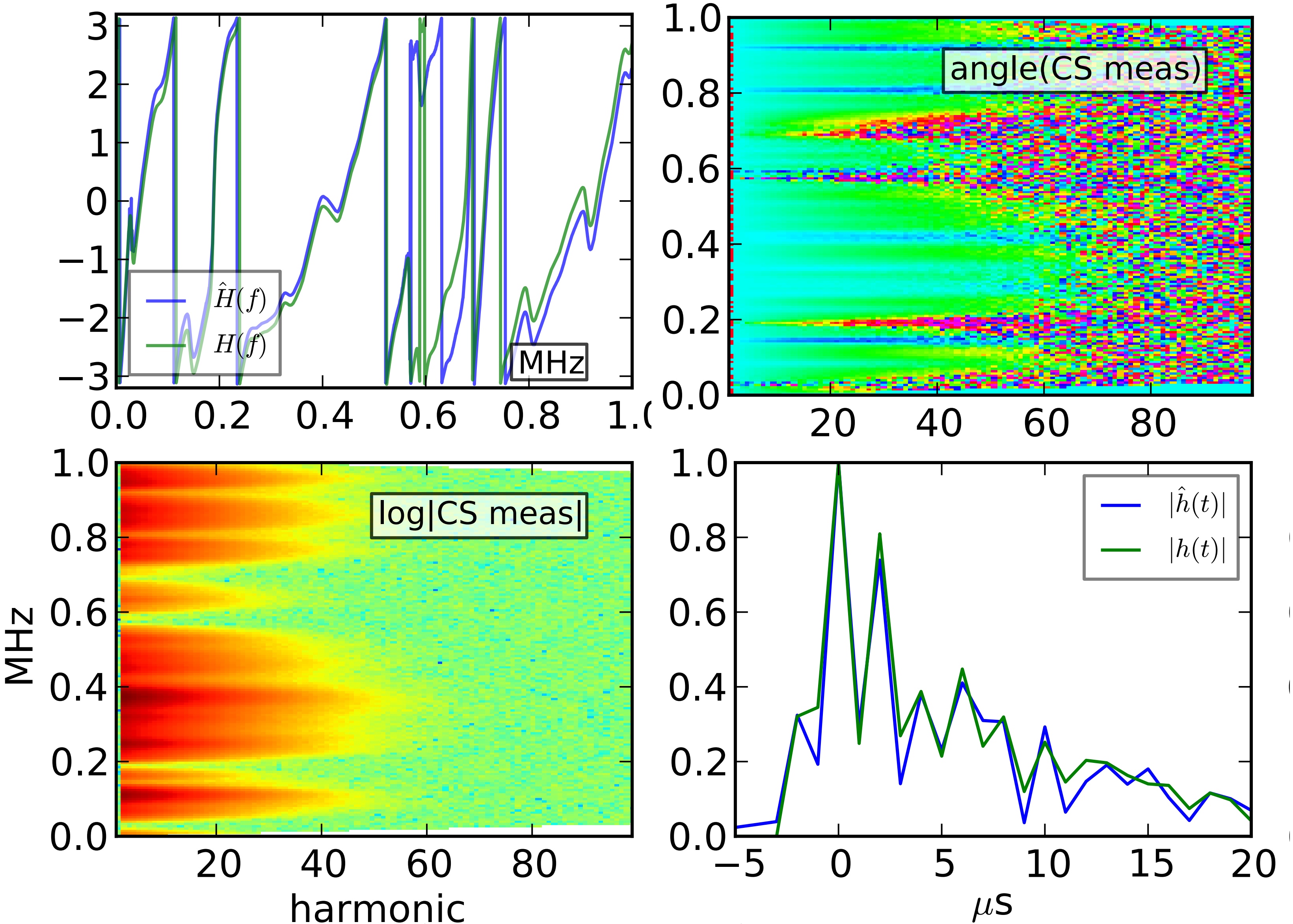
LWA Users Meeting

WDvS algorithm on simulated data: 5μs scattering



WDvS algorithm on simulated data: 5μs scattering



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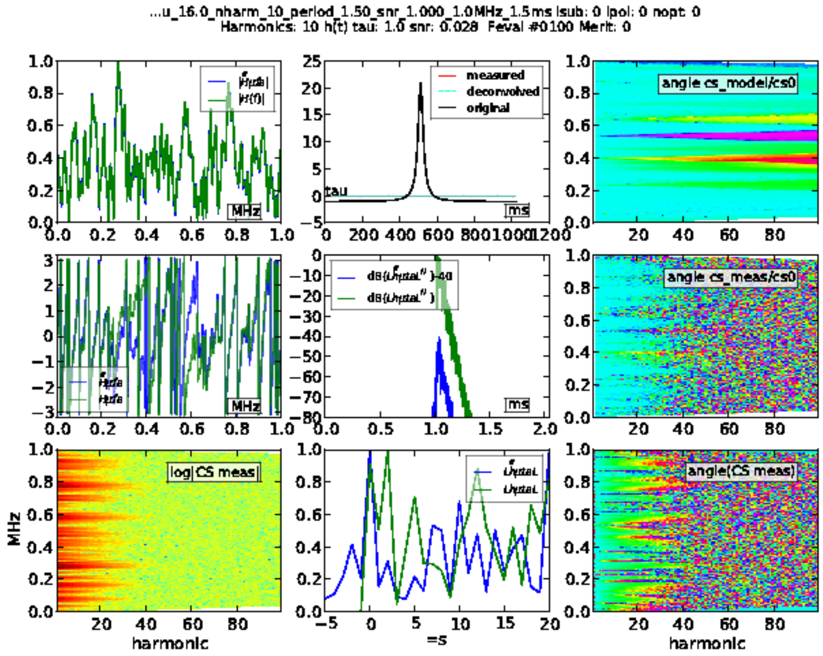
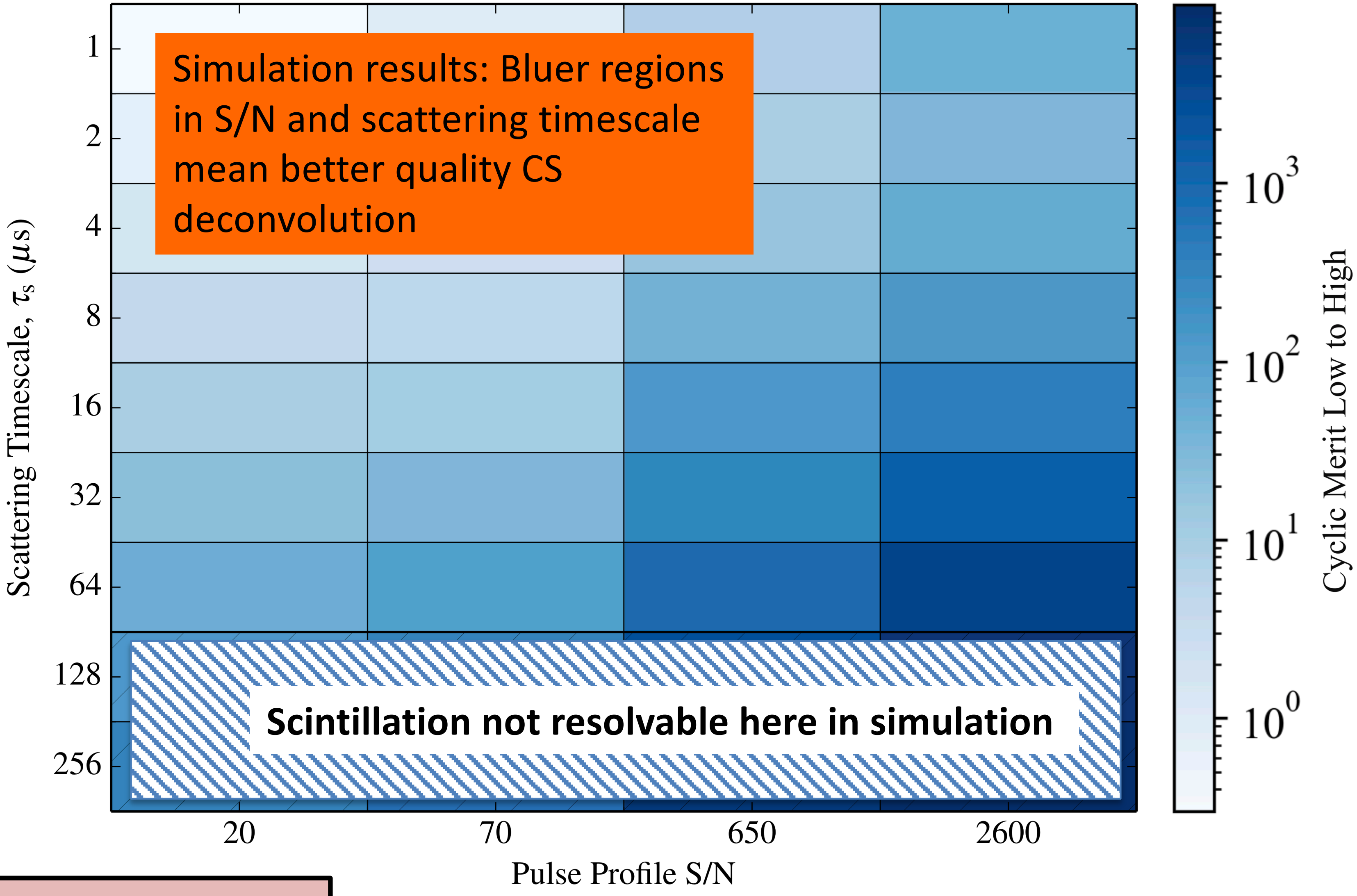
The ISM and Coherent Deconvolution with Cyclic Spectroscopy (CS) https://github.com/gitj/pycyc

- WDvS13 developed a fitting algorithm that separates out the intrinsic pulsar signal from the effects of the interstellar medium
- With some assumptions about the intrinsic (non-scattered) profile, the impulse response function can be iteratively solved for
- The EM phase information preserved in a cyclic spectrum is critical to this process
- Most of the iteration time in the fitting algorithm for a particular scattering configuration is spent on fitting the *phase* of the CS, not the *amplitude*



Dolch et al. 2020 in prep.

Diagnostic for CS deconvolution ability as function of pulse profile S/N and scattering timescale

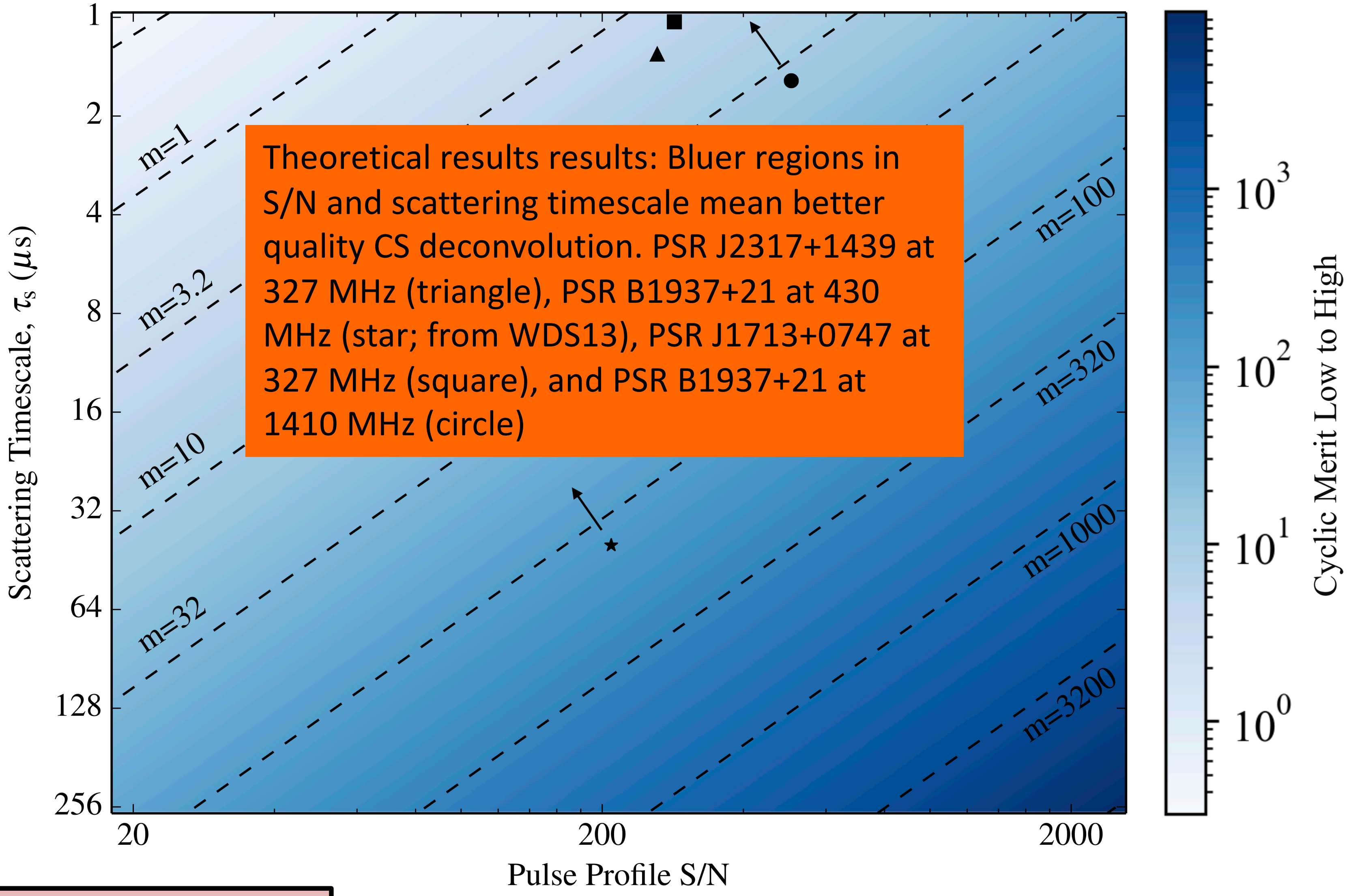


Simulation results: Bluer regions in S/N and scattering timescale mean better quality CS deconvolution

Scintillation not resolvable here in simulation

Dolch et al. 2020 (in prep)

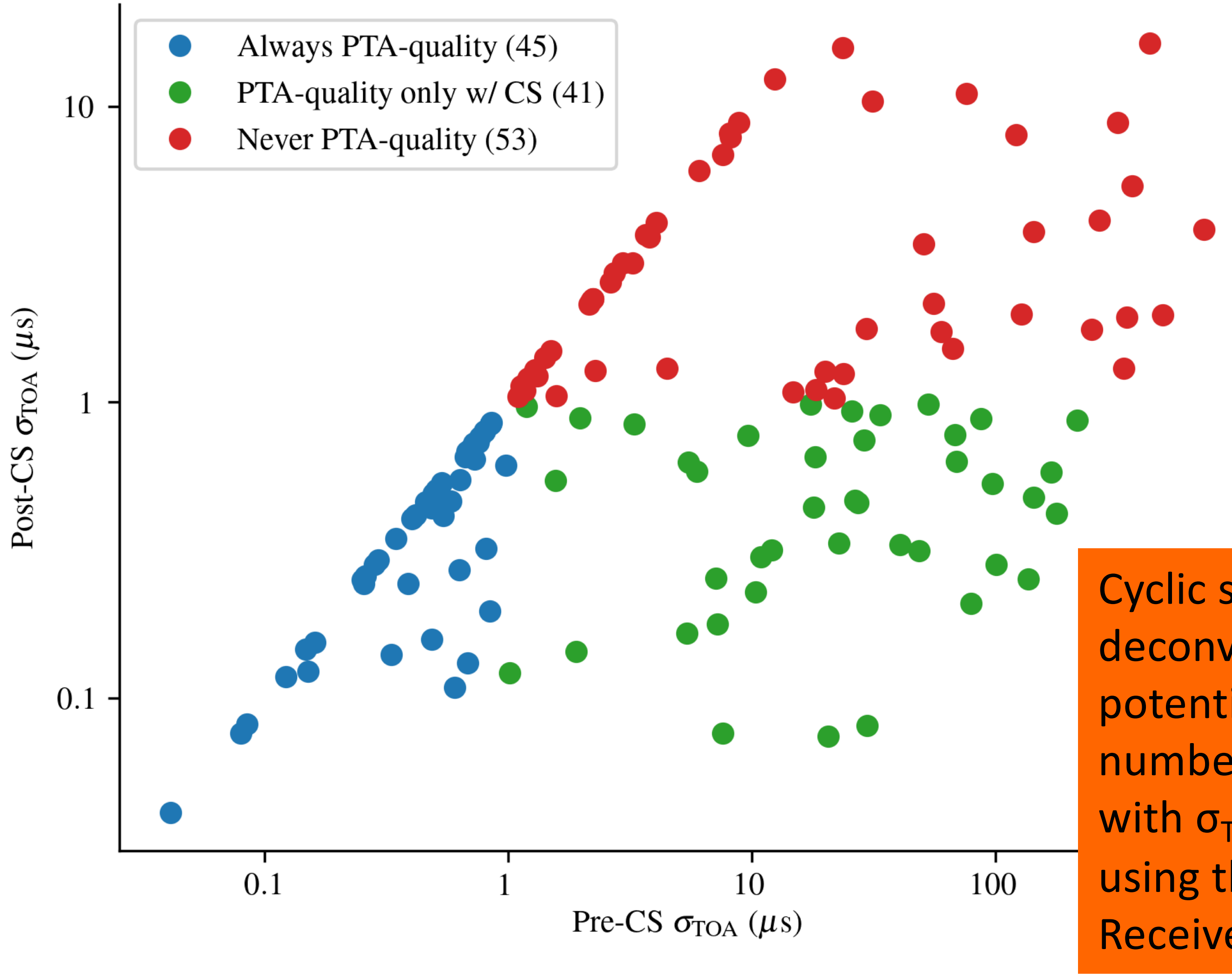
Diagnostic for CS deconvolution ability as function of pulse profile S/N and scattering timescale



Theoretical results results: Bluer regions in S/N and scattering timescale mean better quality CS deconvolution. PSR J2317+1439 at 327 MHz (triangle), PSR B1937+21 at 430 MHz (star; from WDS13), PSR J1713+0747 at 327 MHz (square), and PSR B1937+21 at 1410 MHz (circle)

Dolch et al. 2020 (in prep)

Simulated Pulsars Improved with Cyclic Spectroscopy

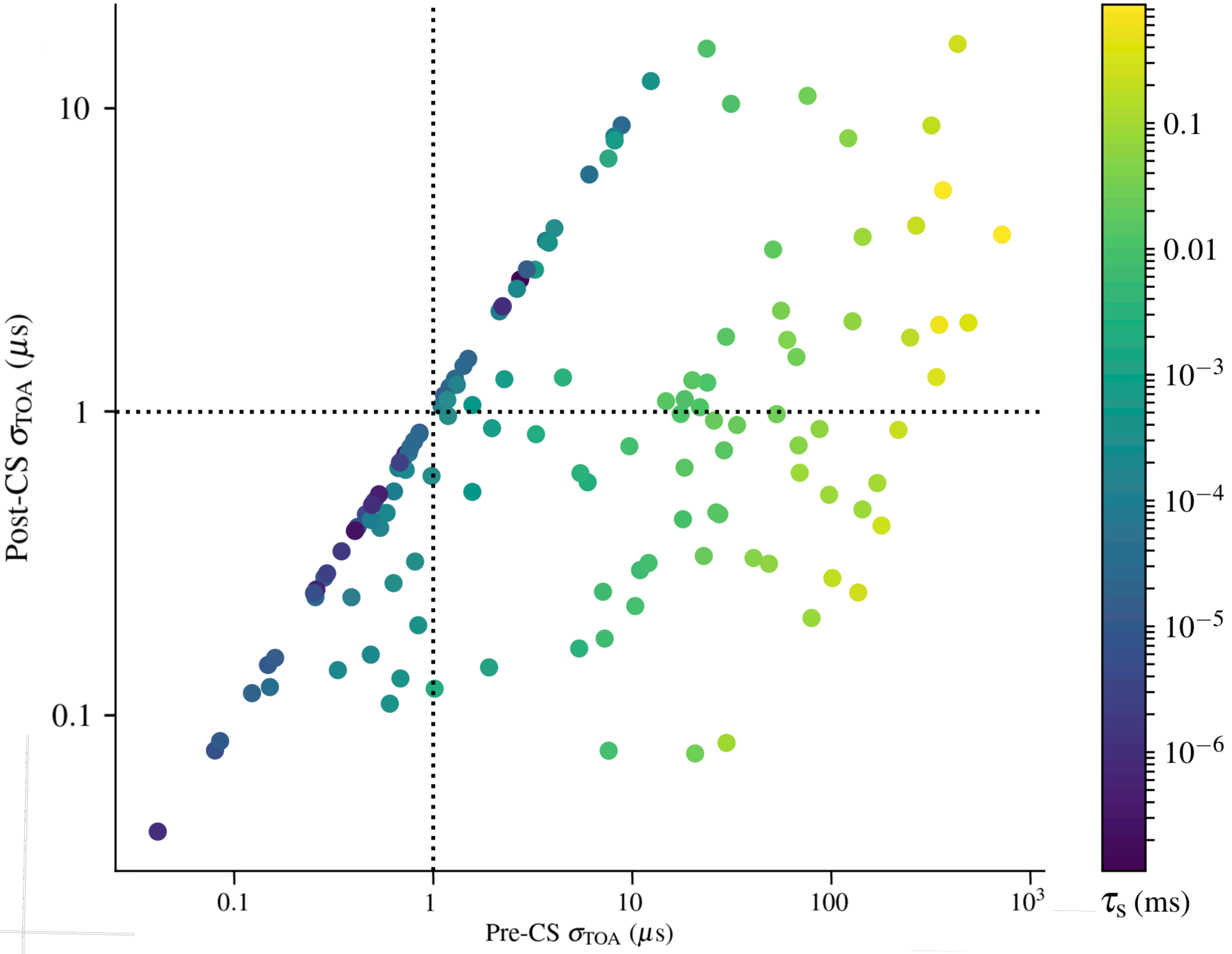


Cyclic spectroscopy deconvolution has the potential to double the number of PTA-quality MSPs with σ_{TOA}<1μs at the GBT using the Ultra-Wideband Receiver under construction.

Dolch et al. 2020 (in prep)

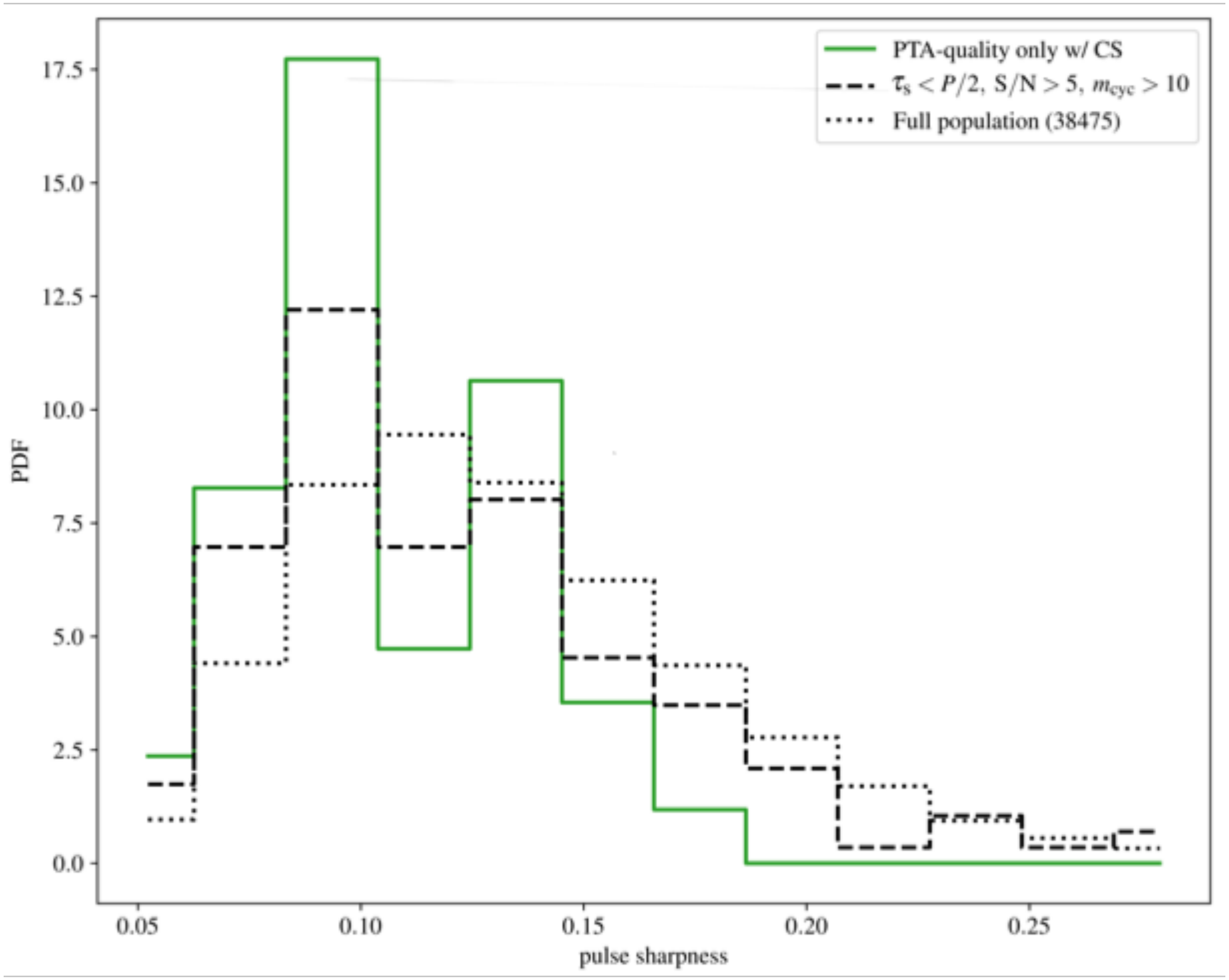
Thanks to T. Cohen, NMTech

Scattering timescales of Simulated Pulsars



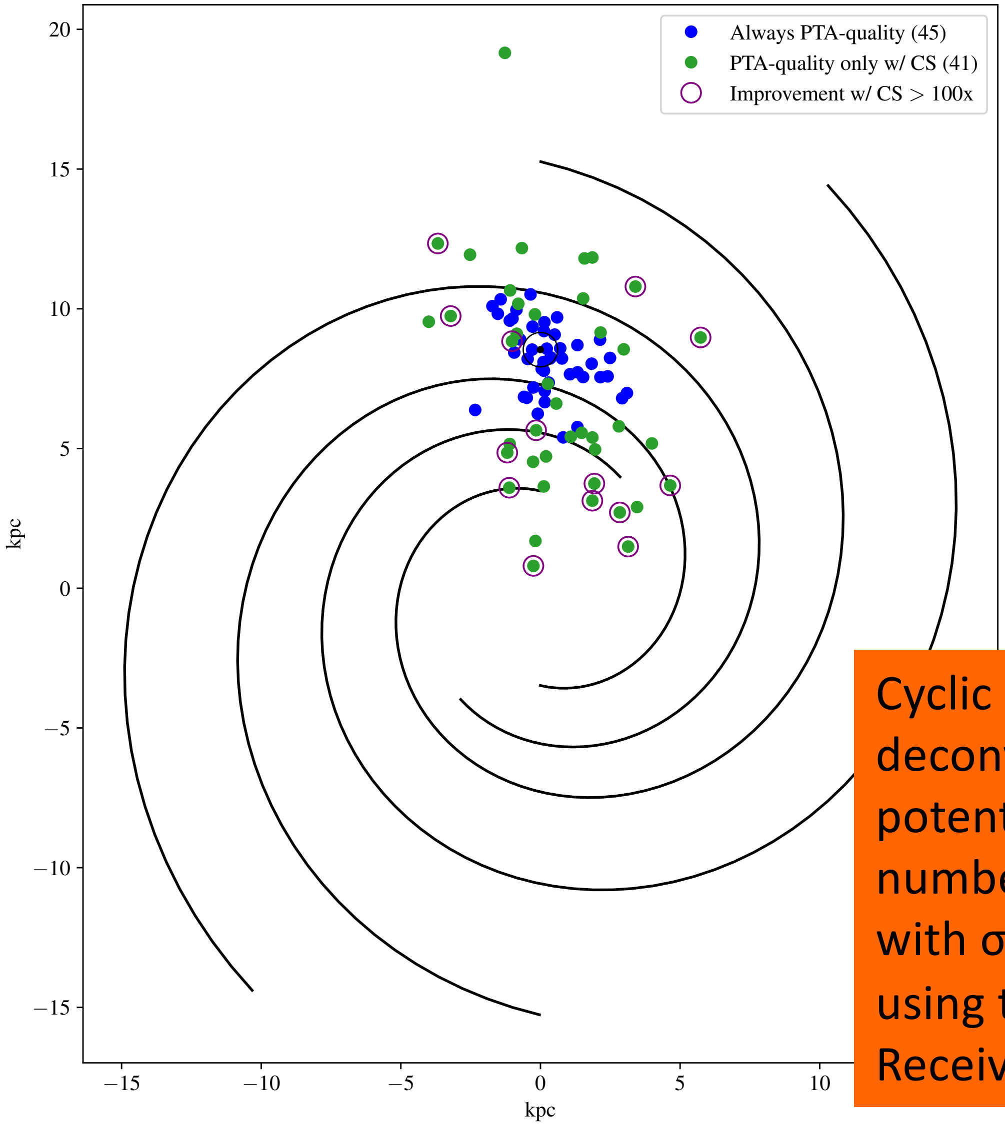
Dolch et al. 2020 (in prep)

Intrinsic Pulse Sharpness of Simulated Pulsars



Dolch et al. 2020 (in prep)

Galactic Distribution of Simulated Pulsars



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Benefits of Cyclic Spectroscopy for (Low-frequency) Radio Astronomy

- Cyclic spectroscopy deconvolution ability (removing ISM effects by fitting for transfer function) may be enabled by higher scattering timescales than most current PTA pulsars
- Future possibility: ISM scattering removal may change some pulsars that are too scattered to be good timers – **GBT Ultra-wideband receiver predicted results may be similar to possible LWA results with cyclic spectroscopy**
- In other words, high scattering might help us. Especially in future telescopes: either low-frequency telescopes with seeing high scattering tails (LWA-Swarm, SKA-low) or higher-frequency, highly sensitive telescopes (ngVLA, SKA-mid)
- Can also provide extremely fine frequency resolution for a pulsed signal, for better RFI mitigation or scattering tail resolution (as in Archibald, Hessels, & Stinebring 2014 with LOFAR)
- Used in VLITE data for RFI mitigation with pulsed RFI as signal (Kerr, private communication)