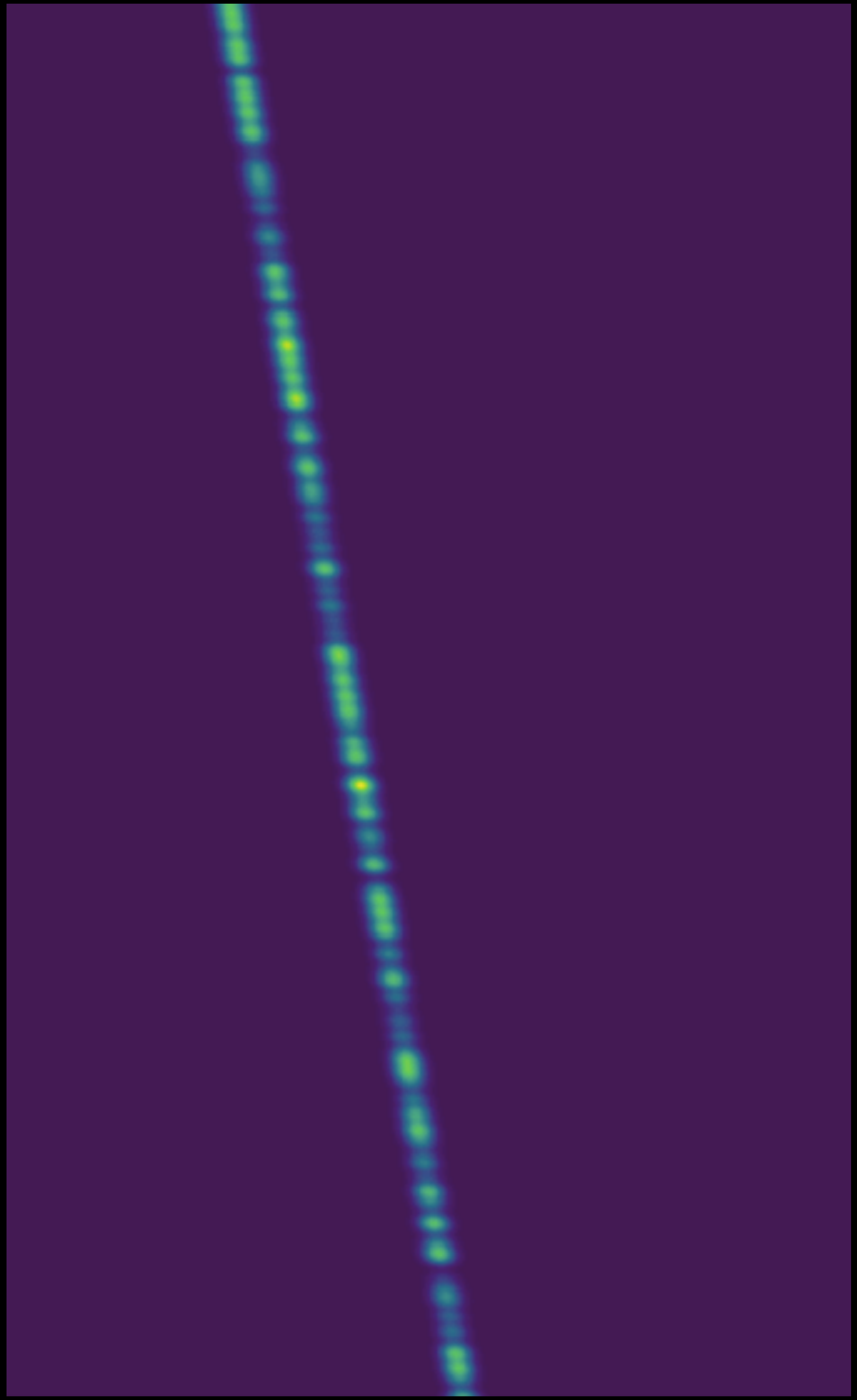


BREAKTHROUGH
LISTEN

A Narrowband Search for Scintillated Signals near the Galactic Center

Bryan Brzycki

University of California Berkeley

Breakthrough Advisory, June 27, 2023

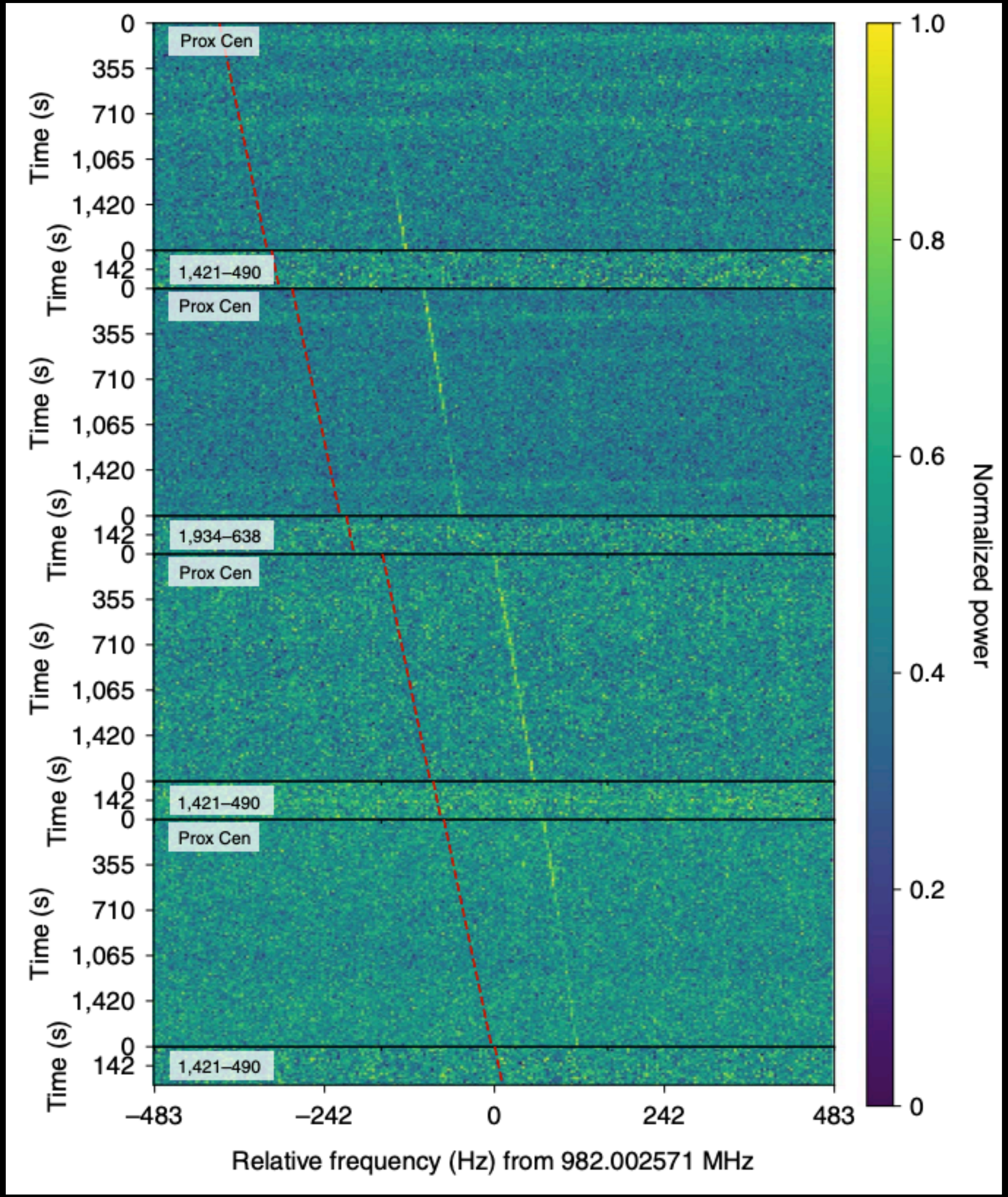
BERKELEY SETI
RESEARCH CENTER

Can we use astrophysical phenomena as a way to distinguish technosignatures from RFI?

ESA

Standard filters used for radio technosignature candidates

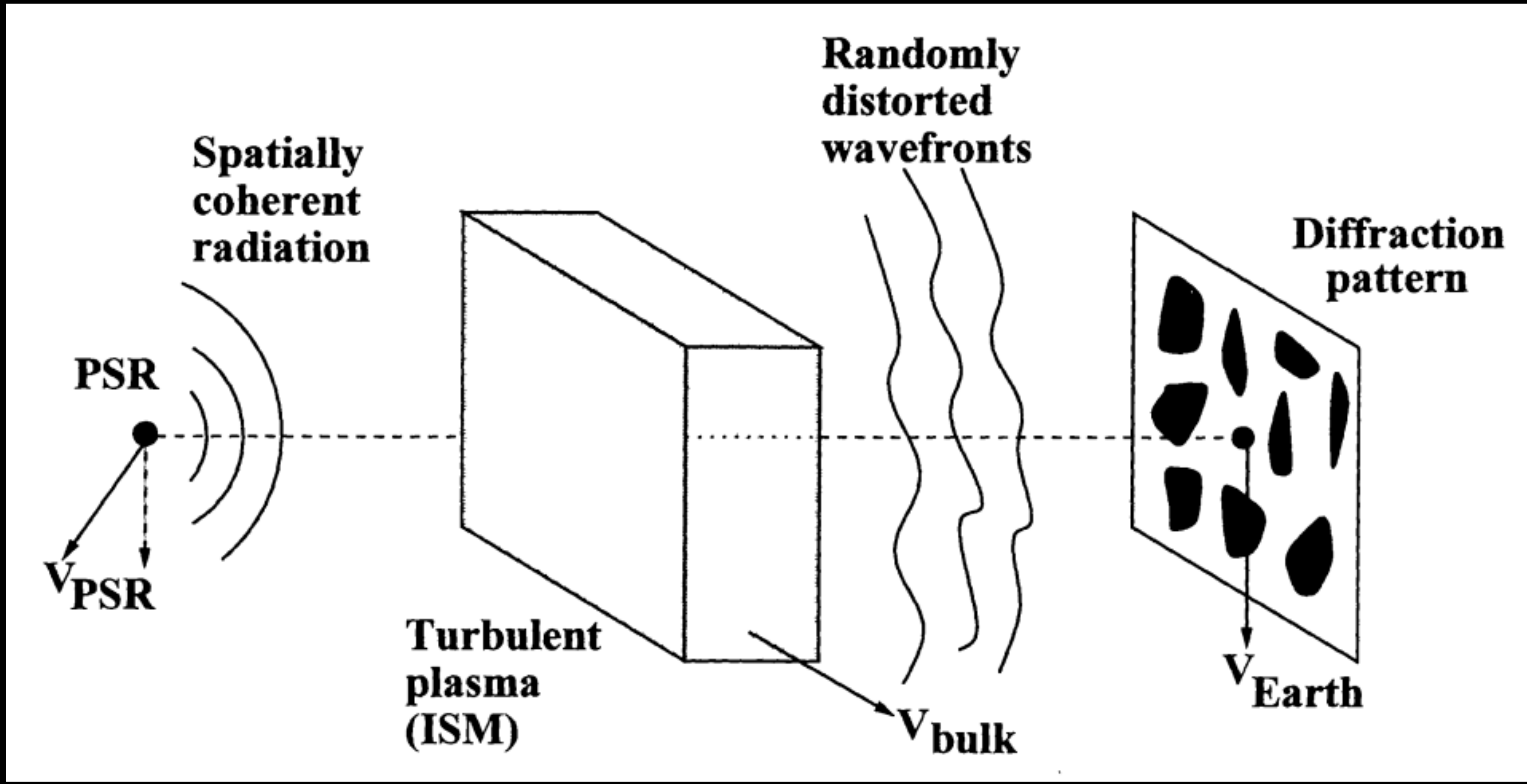
- **Narrowband** vs. astrophysical sources
- **Non-zero drift rate** vs. RFI
- **Sky localization** vs. RFI



Smith et al. 2021

Diffractive scintillation in the ISM

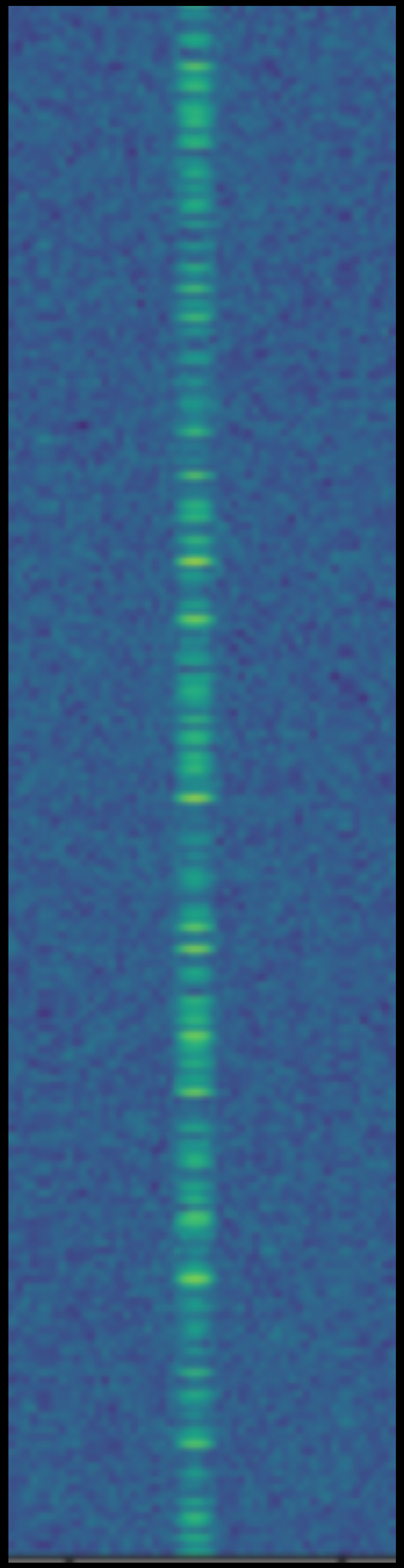
- Electron density fluctuations in ionized plasma creates interference pattern
- Can lead to 100% intensity modulation, especially towards the Galactic center, with characteristic temporal scales Δt_d



Cordes 2002

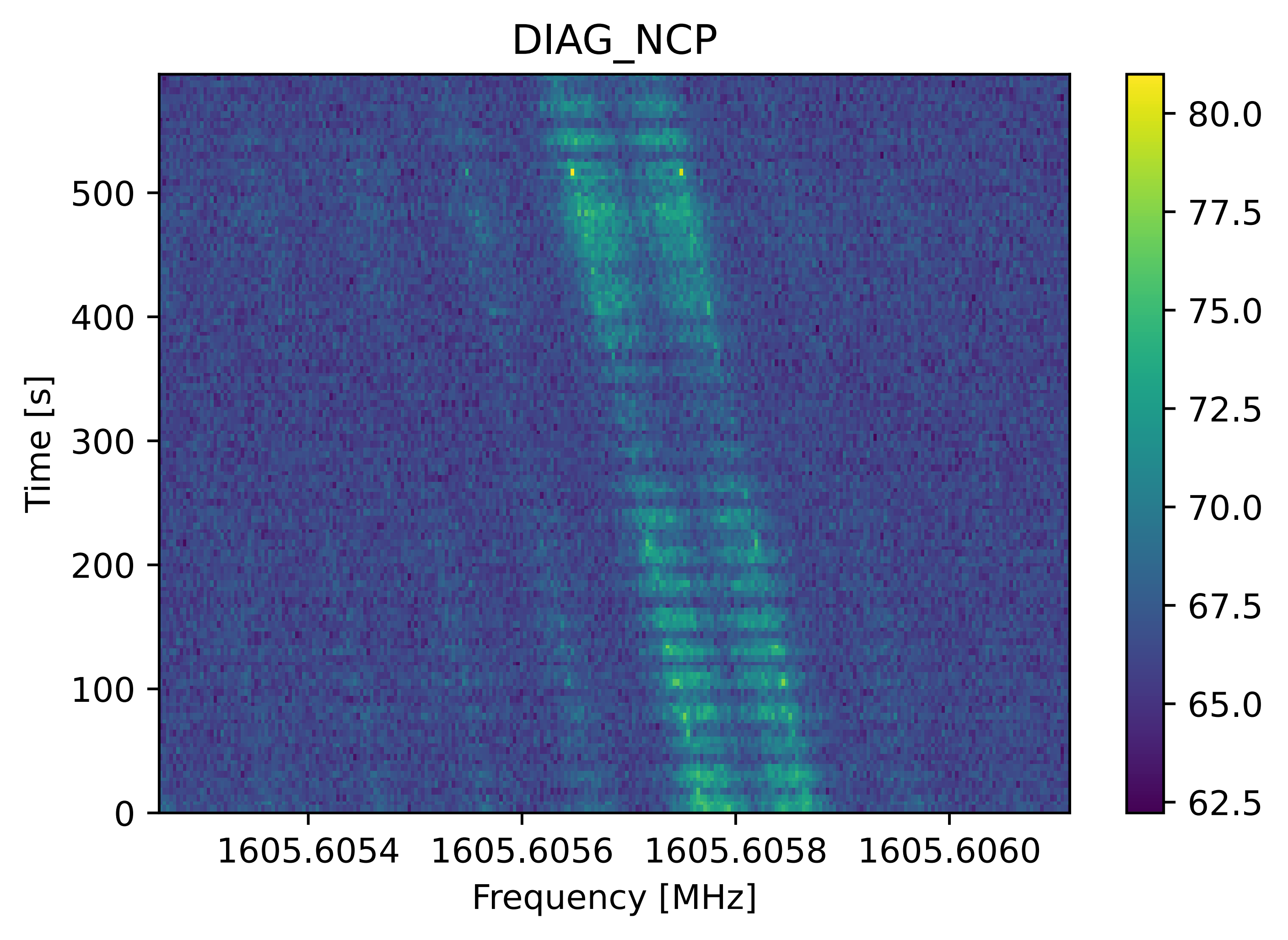
Why scintillation?

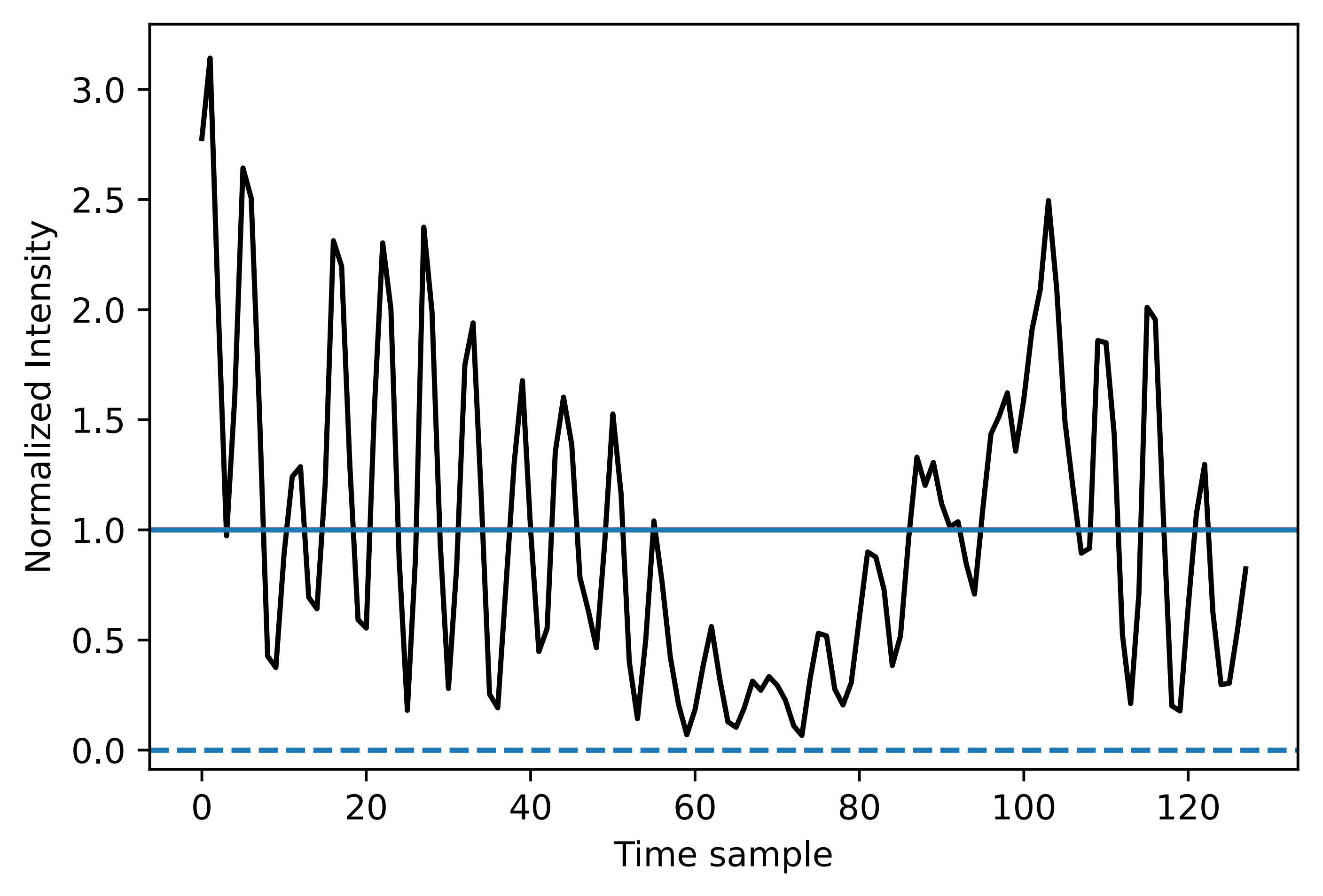
- A filter that directly implies extra-solar origin
- Well-suited for continuous or pulsed *narrowband* signals
- One of the best places to search for scintillation corresponds to one of the best places to look for ETI — the Galactic center

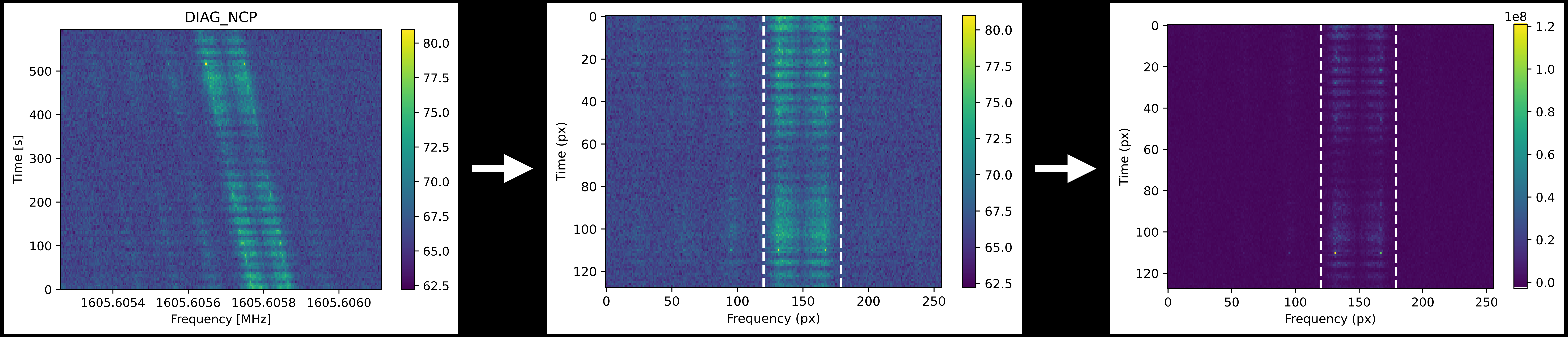


How might we detect scintillation? (Brzycki et al. 2023, accepted to ApJ)

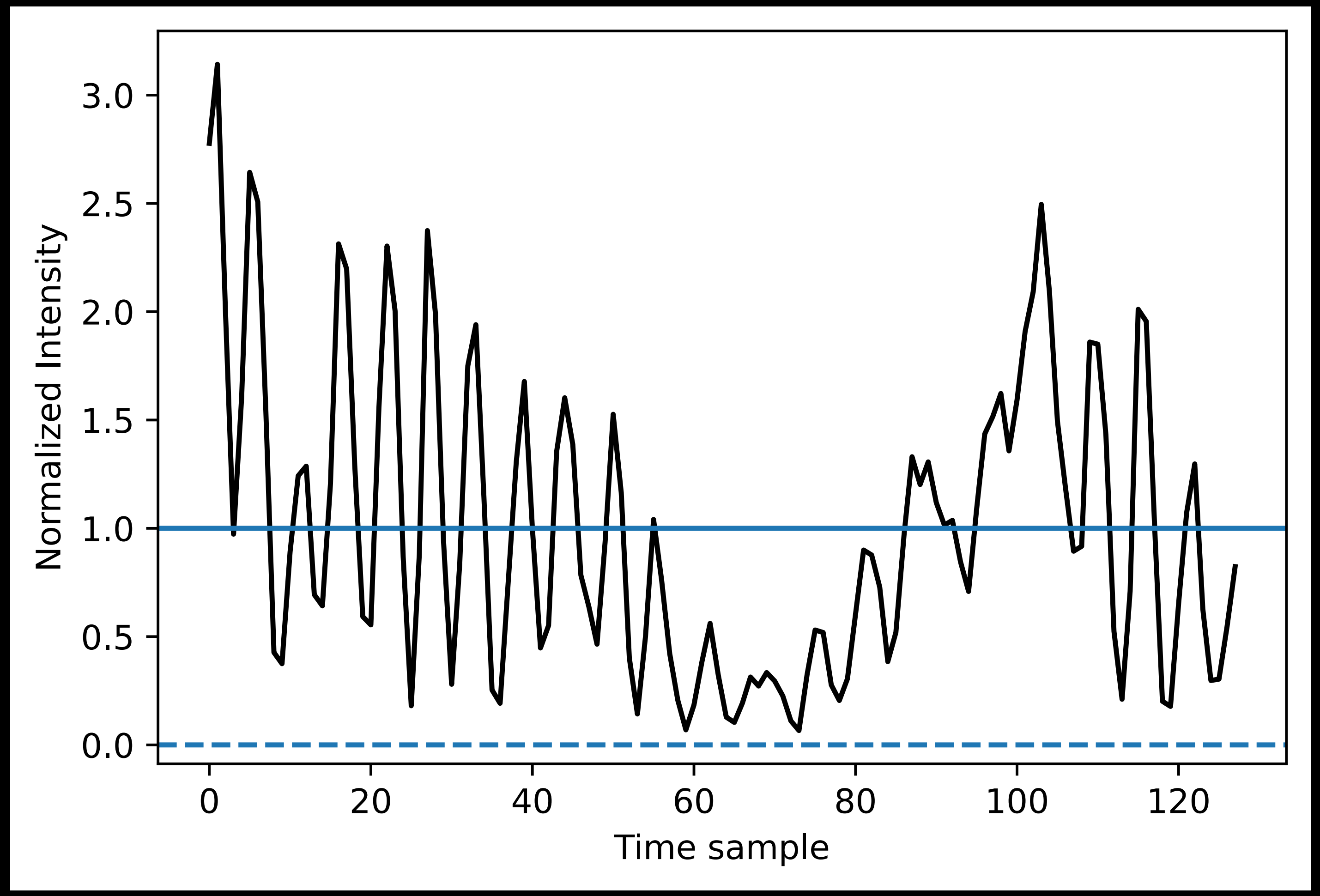
- Estimate intensity time series from signals detected with deDoppler methods
- Since scintillation is stochastic, identify **measurable statistics** for asymptotic behavior
- Would existing RFI modulation confound real scintillation?
    - Methods for creating synthetic scintillated intensities
    - Compare statistics of detected signals with those of synthetic scintillated signals



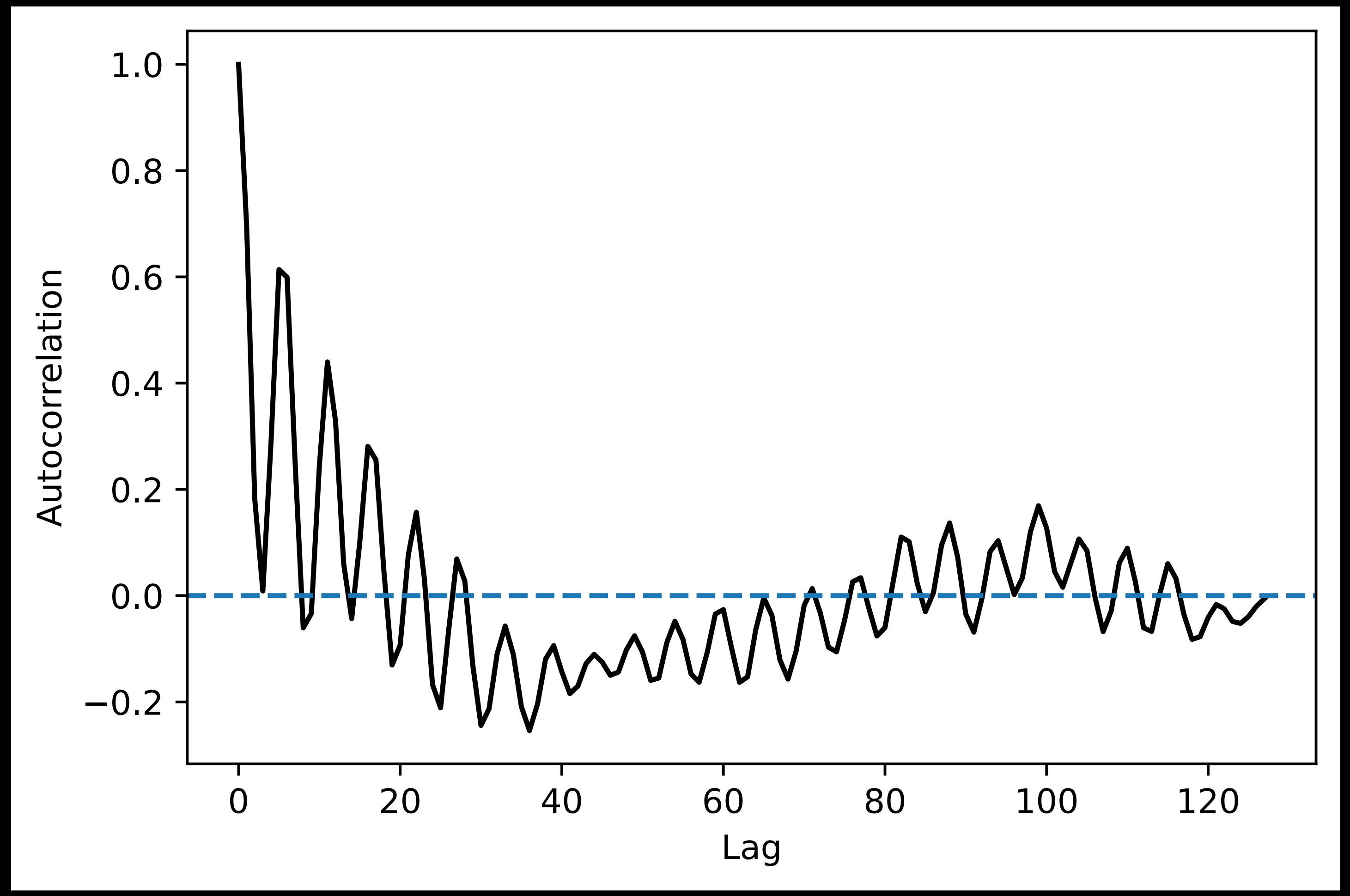




Normalized intensity over time



Autocorrelation function

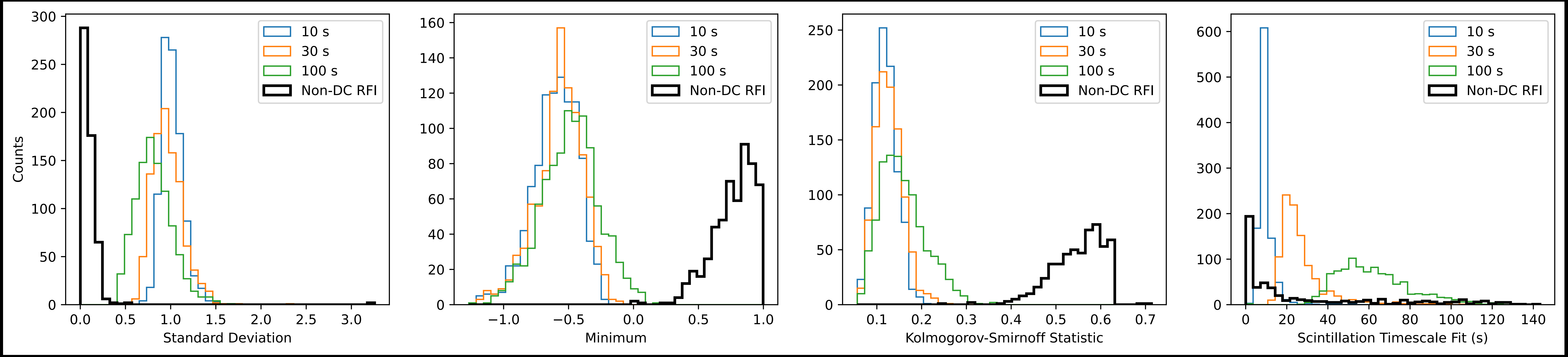


→ Diagnostic statistics

GBT RFI vs. synthetic scintillated signals

C band

S/N > 25



Standard Deviation

Minimum

Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

GBT RFI vs. synthetic scintillated signals

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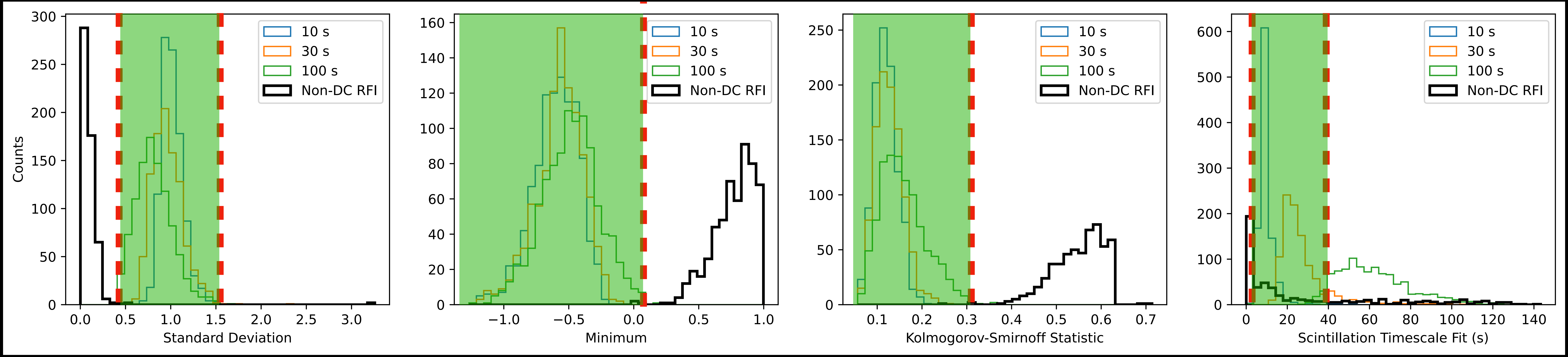


Standard Deviation

Minimum

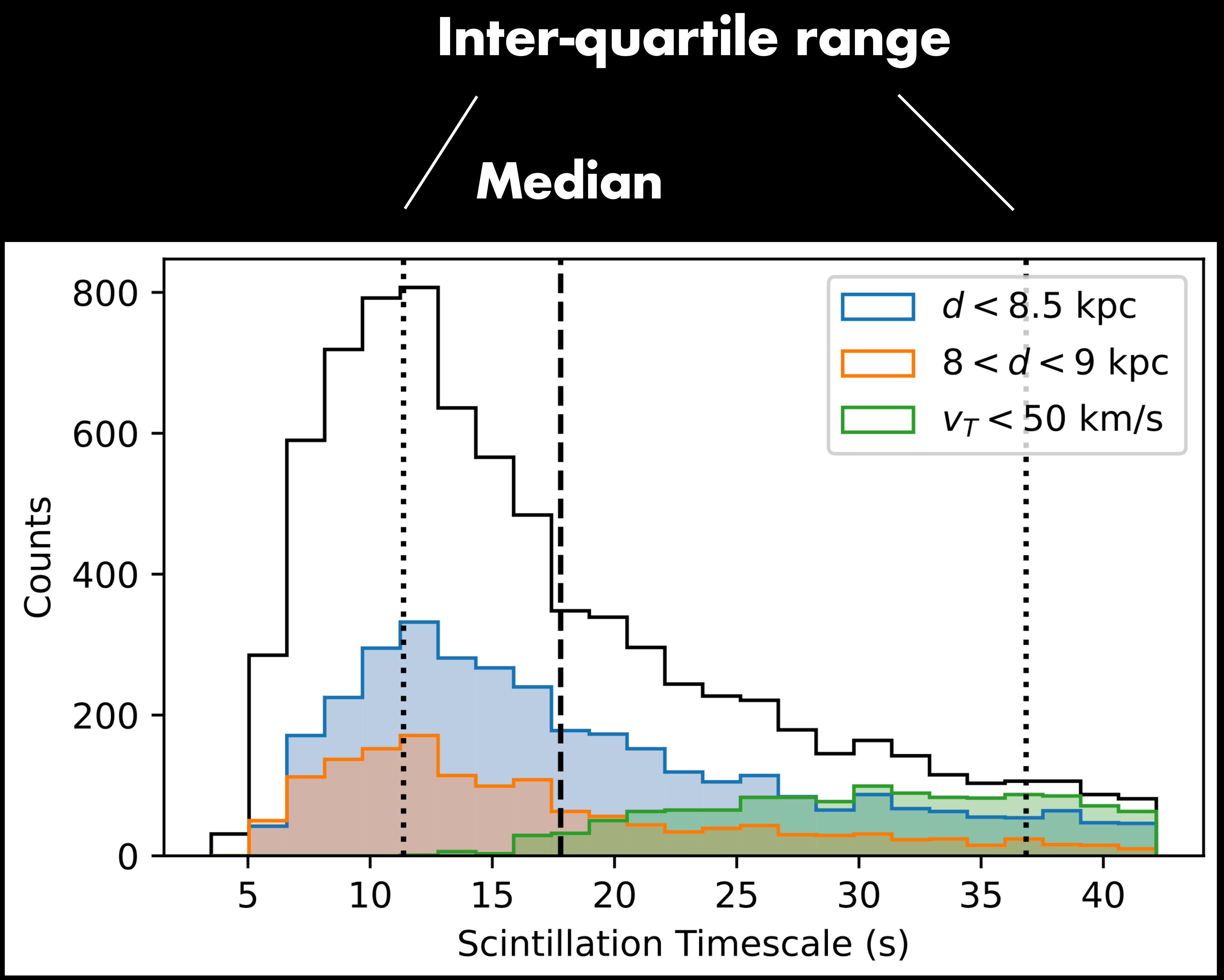
Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

Planning Galactic Center observations — Monte Carlo sims with NE2001

- Estimate scintillation timescales with NE2001 (Cordes & Lazio 2002) and scale with different sets of parameters
    - Galactic coordinates
    - Distance
    - Frequency
    - Transverse velocities

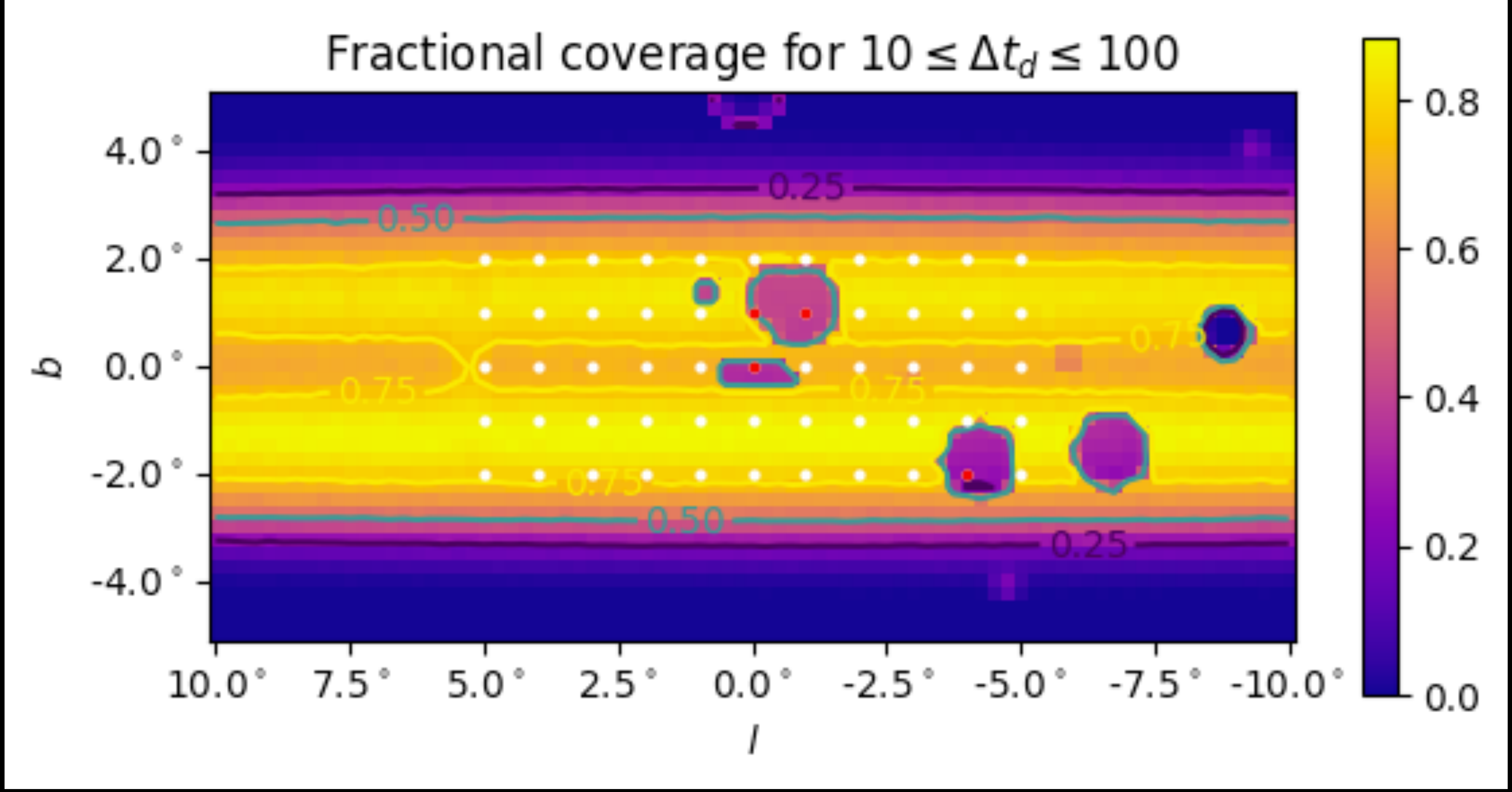
- Monte Carlo sample to characterize the most probable scintillation timescales



(l, b) = (5, 0) at C-band

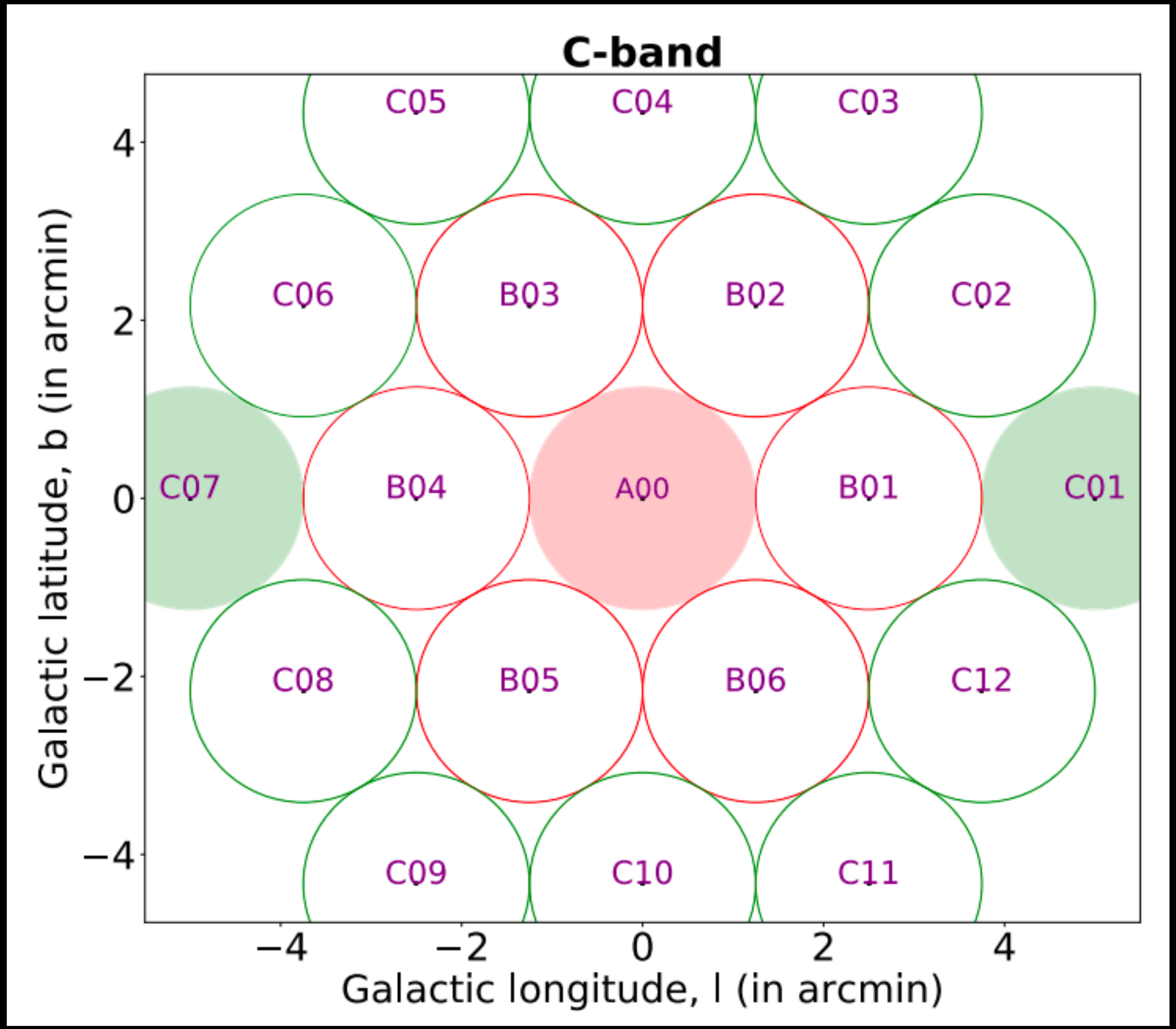
Current observing plan for scintillation survey of the Galactic center

- Galactic plane survey: 54 pointings, with |l| < 5 deg, |b| < 2 deg



Current observing plan for scintillation survey of the Galactic center

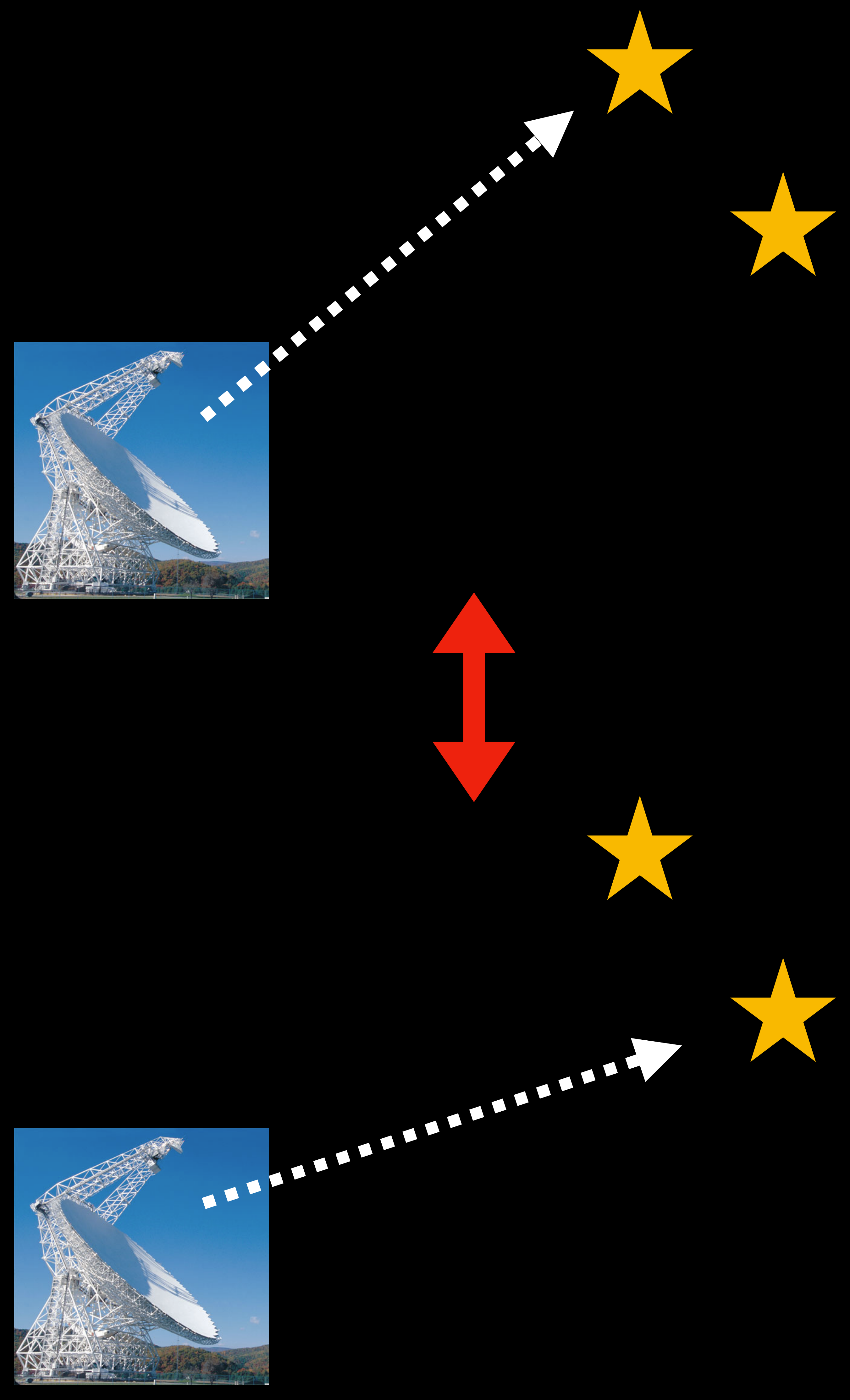
- Galactic center survey: 19 pointings (following Gajjar et al. 2021)



Gajjar et al. 2021

Current observing plan for scintillation survey of the Galactic center

- ABAB cadences
- 10 minutes per observation, so each pointing gets 20 minutes total
- 2.5 s, 2.8 Hz resolution
- Start each observing session with single pointing of North Galactic Pole as probe of local RFI environment



NRAO

Next Steps

- Currently, we have data for 16 out of 27 cadences of the Galactic plane survey, about 12 hours of data
    - 11 GP cadences and 9 GC cadences remain
- Filter collected data using established ON-OFF search methods and perform scintillation analysis
- Ultimate goal is to comment on the prevalance of scintillated technosignatures, as well as the prevalence of RFI that might pass the scintillation thresholds

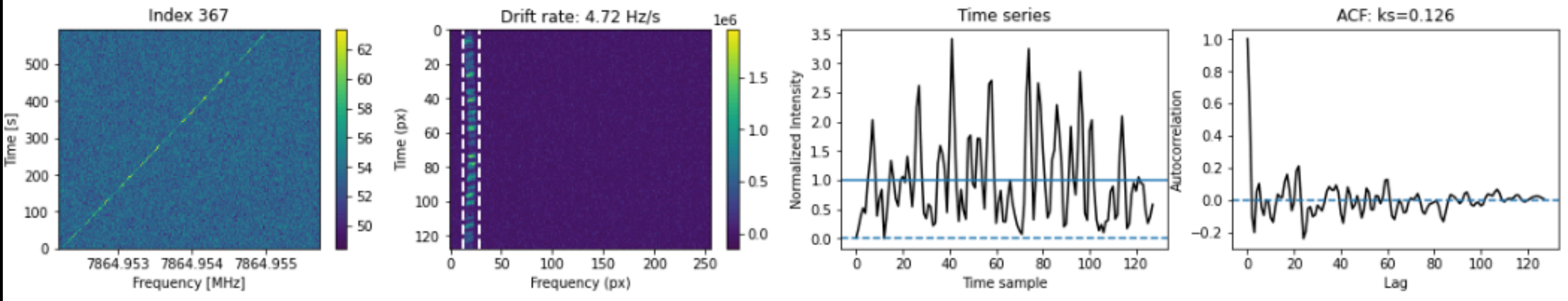
Summary

- We developed a scintillation analysis framework, with accompanying codebase
- We can set statistical filter thresholds based on synthetic signals and the local RFI environment
- We've planned a survey to search for scintillated signals towards the Galactic center / plane, which is well under way

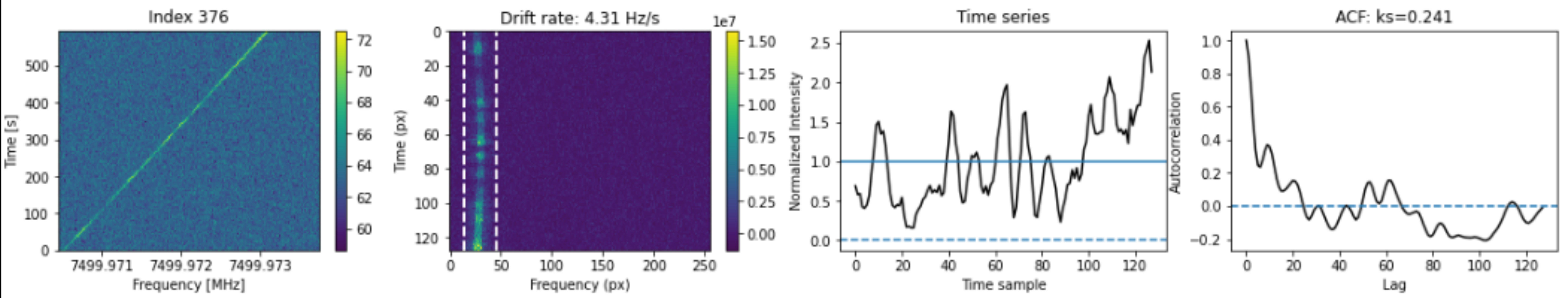
Thank you!

Extra Slides

What signals pass these thresholds?



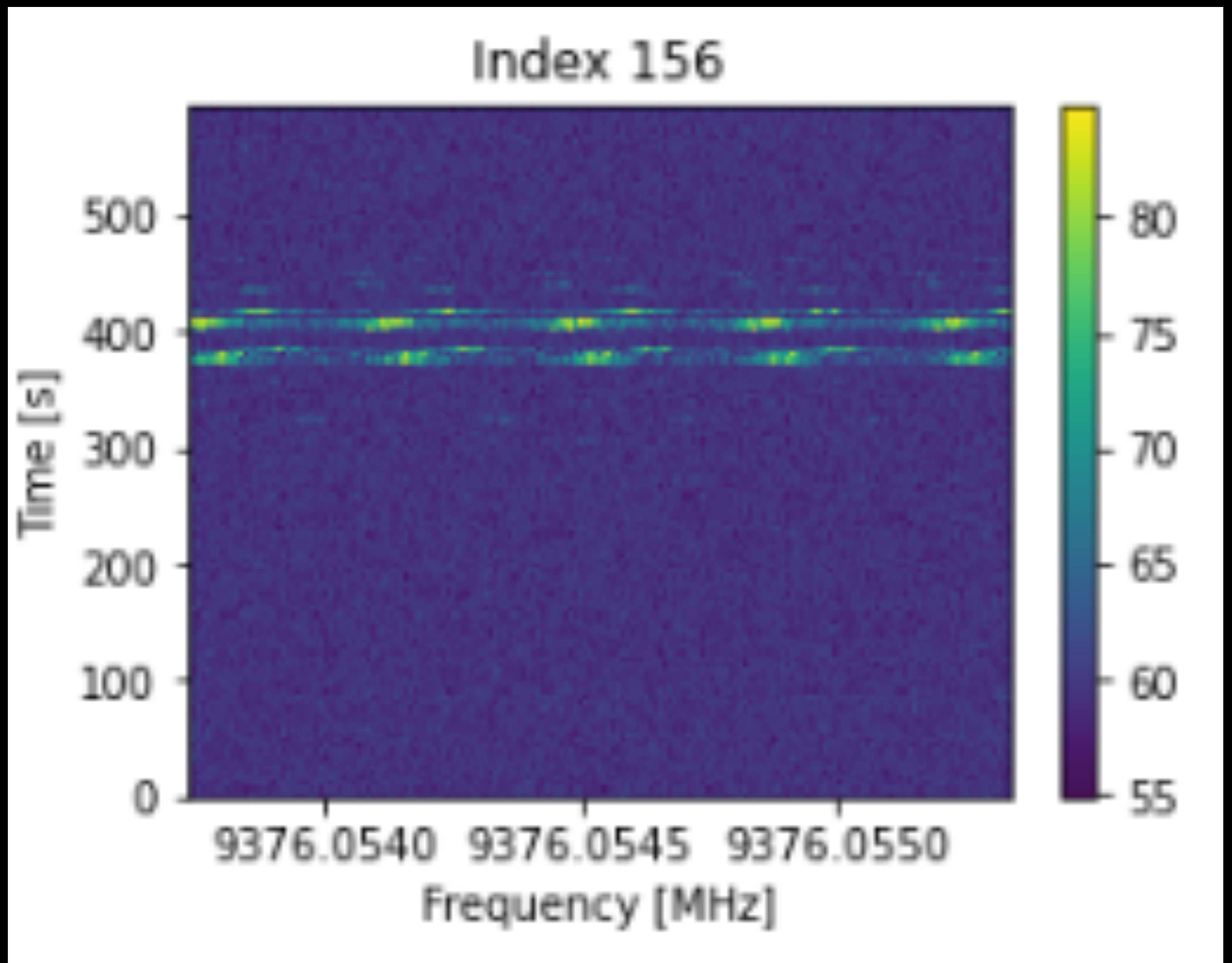
Timescale fit ~ 2 s

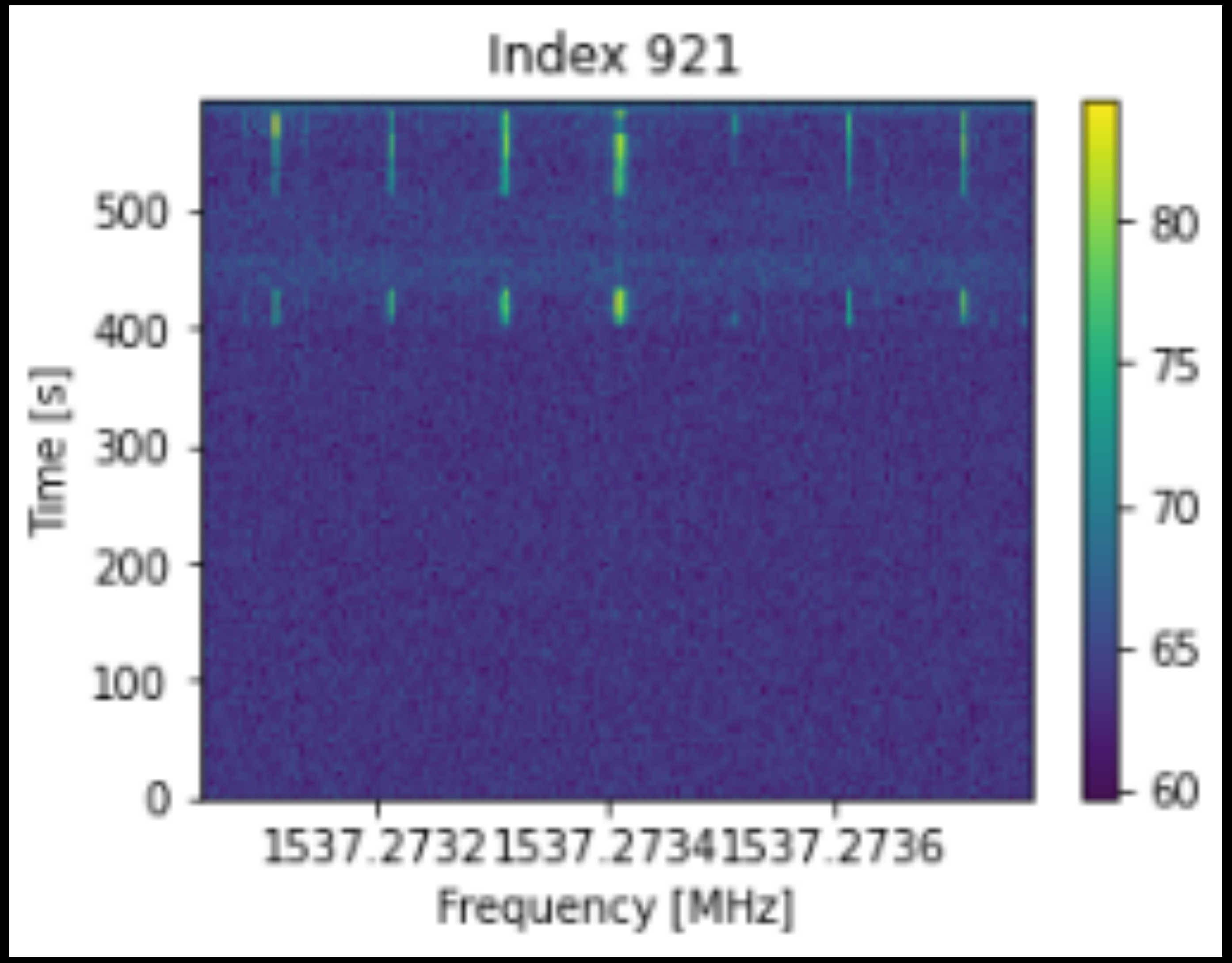


Timescale fit ~ 60 s

Limitations from RFI analysis

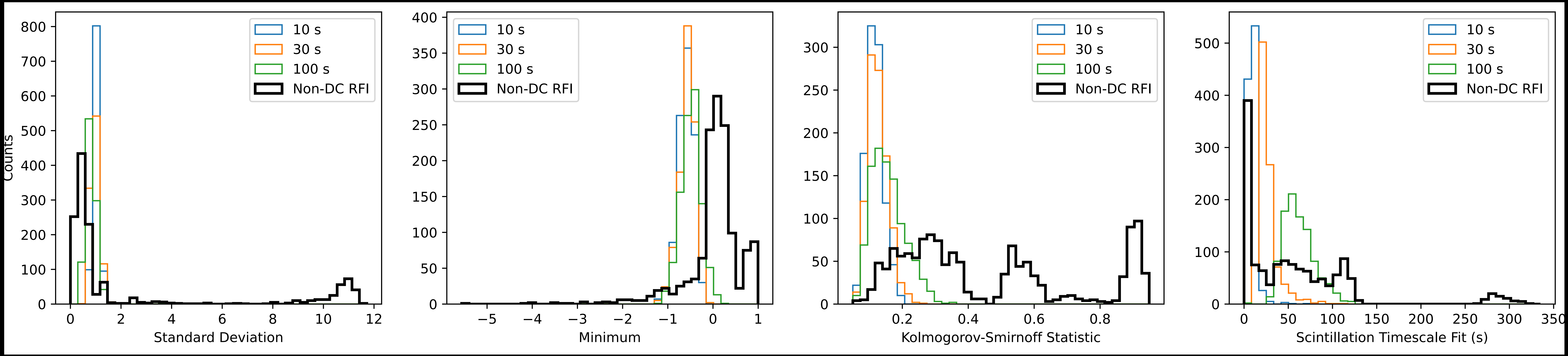
- L and S bands in particular are very noisy
- Non-narrowband signals detected just because they are above the SNR threshold
- Difficult to apply a one-size-fits-all bounding box method
- Perhaps ML can help!





L band

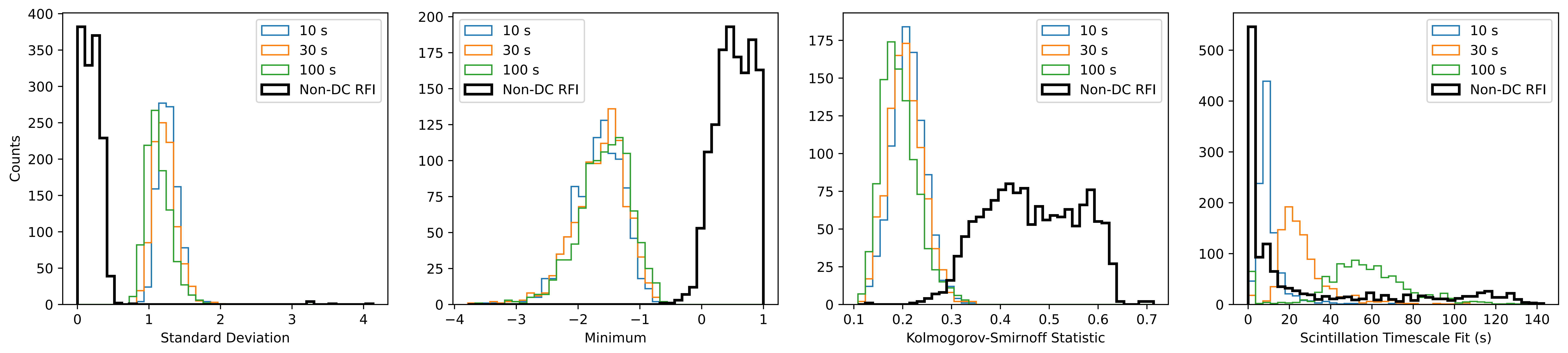
S/N = 25



Std. Dev.   Minimum   KS Statistic   Timescale Fit

C band

S/N = 10



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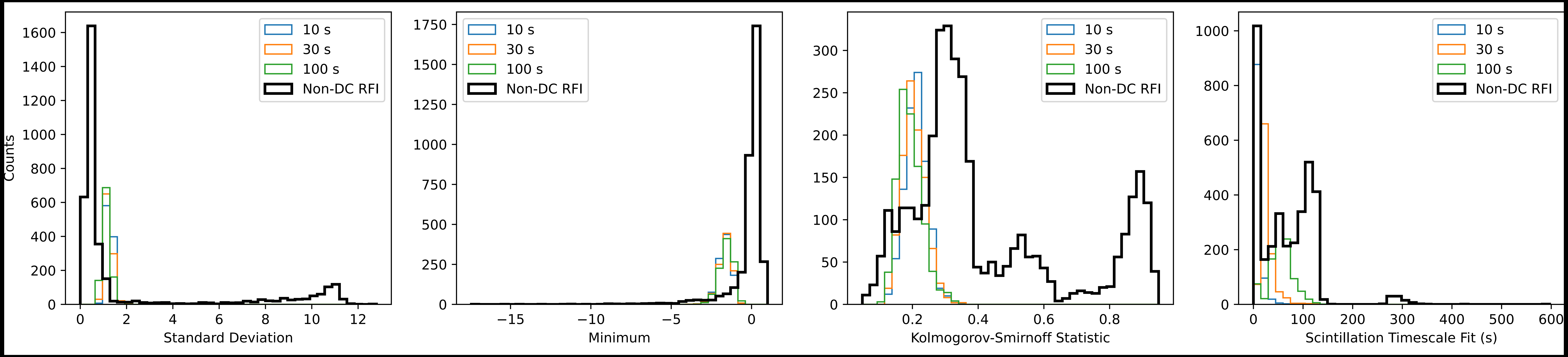
BREAKTHROUGH LISTEN

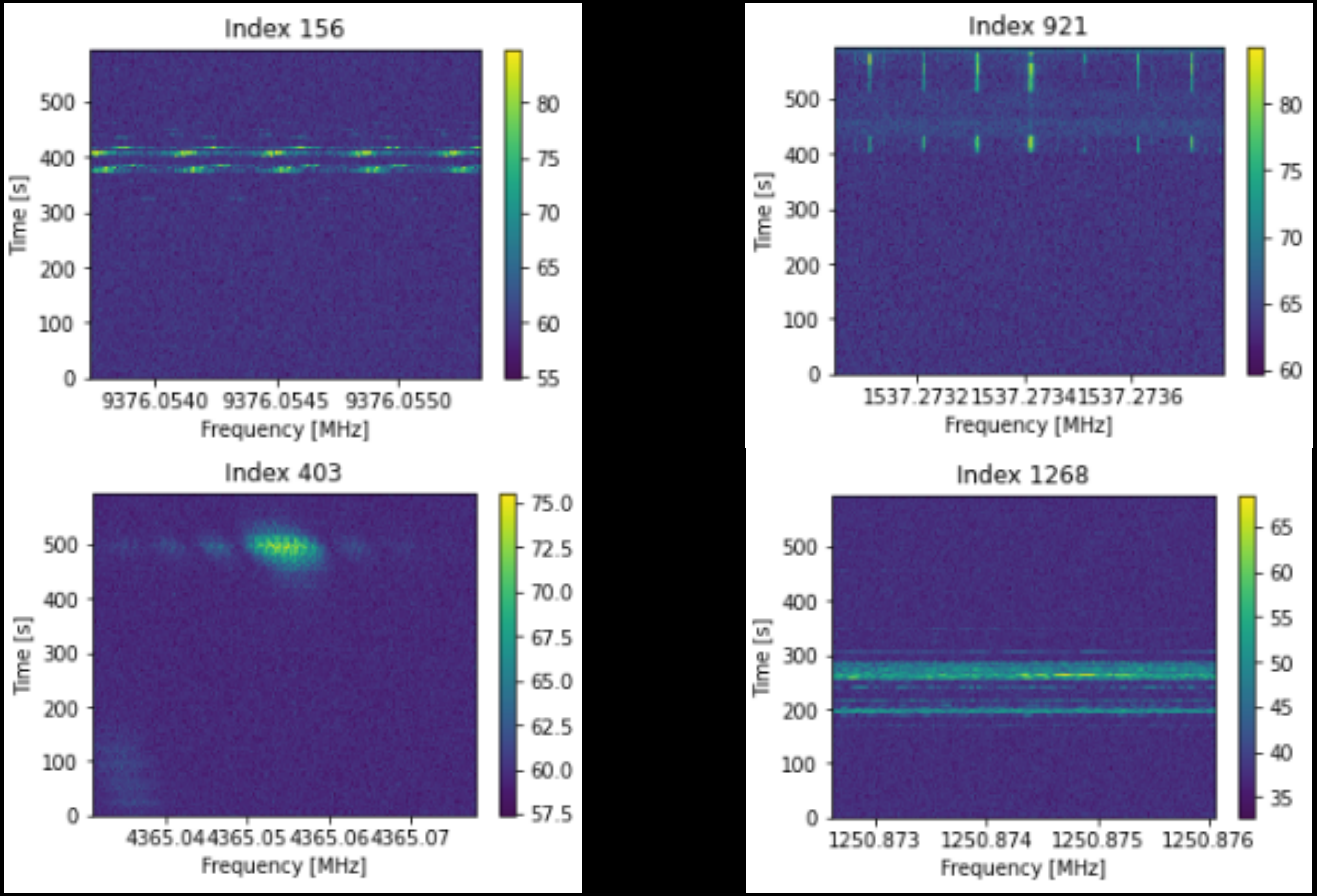
L band

S/N = 10



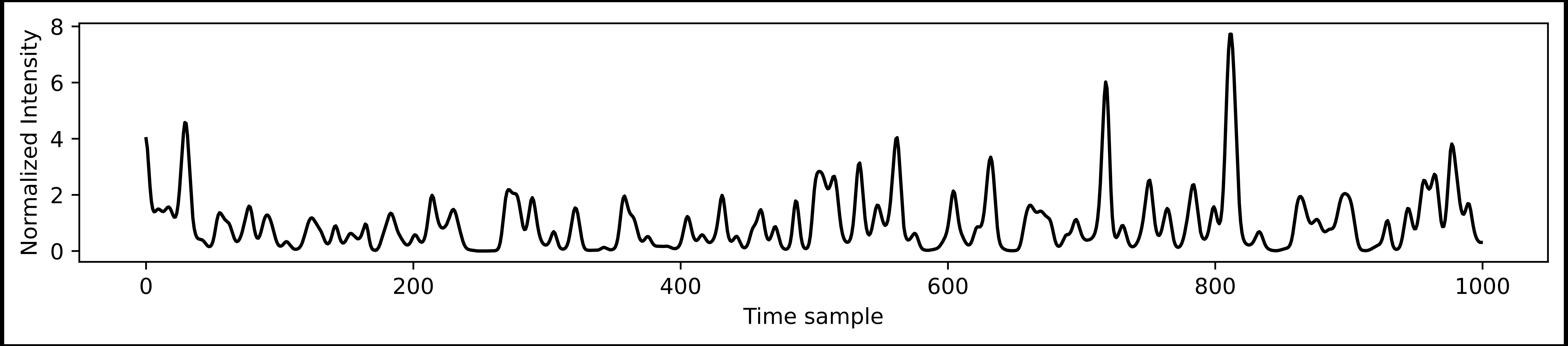
Counts
10 s
30 s
100 s
Non-DC RFI
Standard Deviation
Minimum
Kolmogorov-Smirnoff Statistic
Scintillation Timescale Fit (s)

High standard deviation (RMS) signals are pulsed - or broadband



Quick way to produce synthetic data with asymptotic statistics

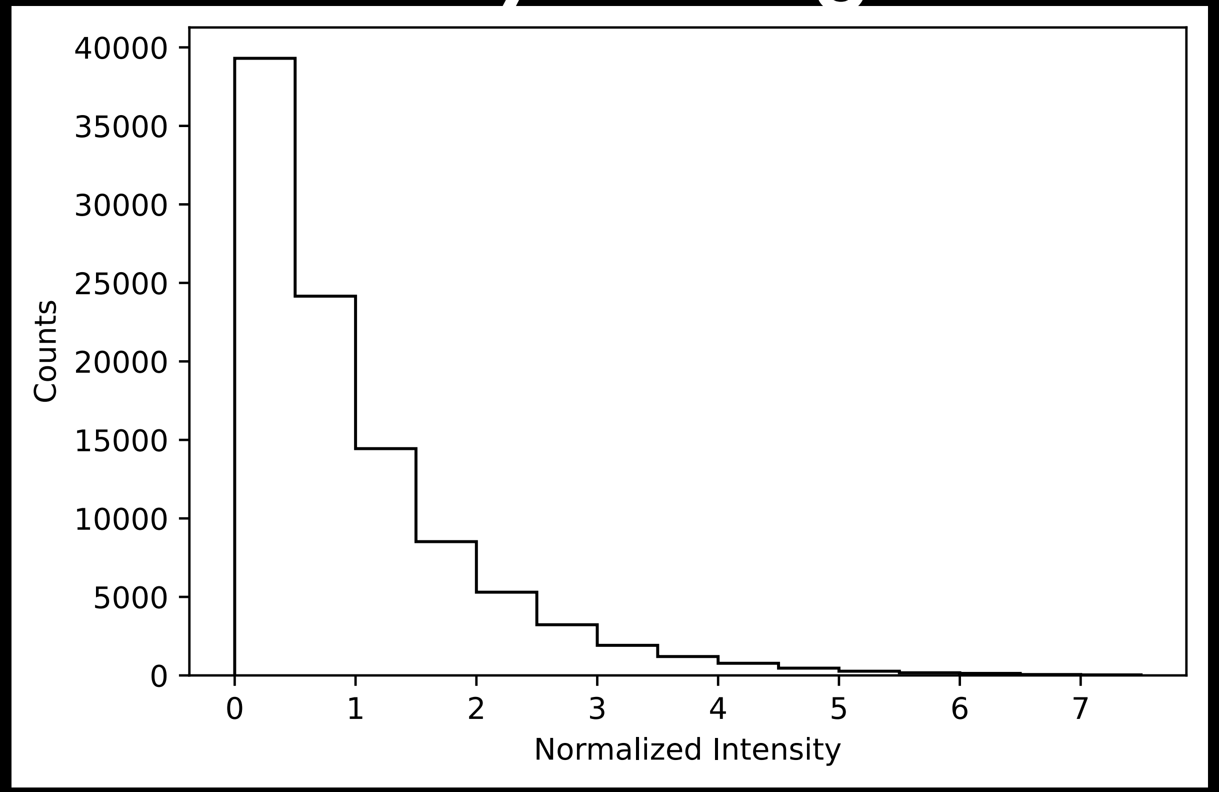
- (Cario & Nelson 1996) The ARTA random process matches:
  - Target intensity distribution
  - Target autocorrelation structure (with custom asymptotic precision)



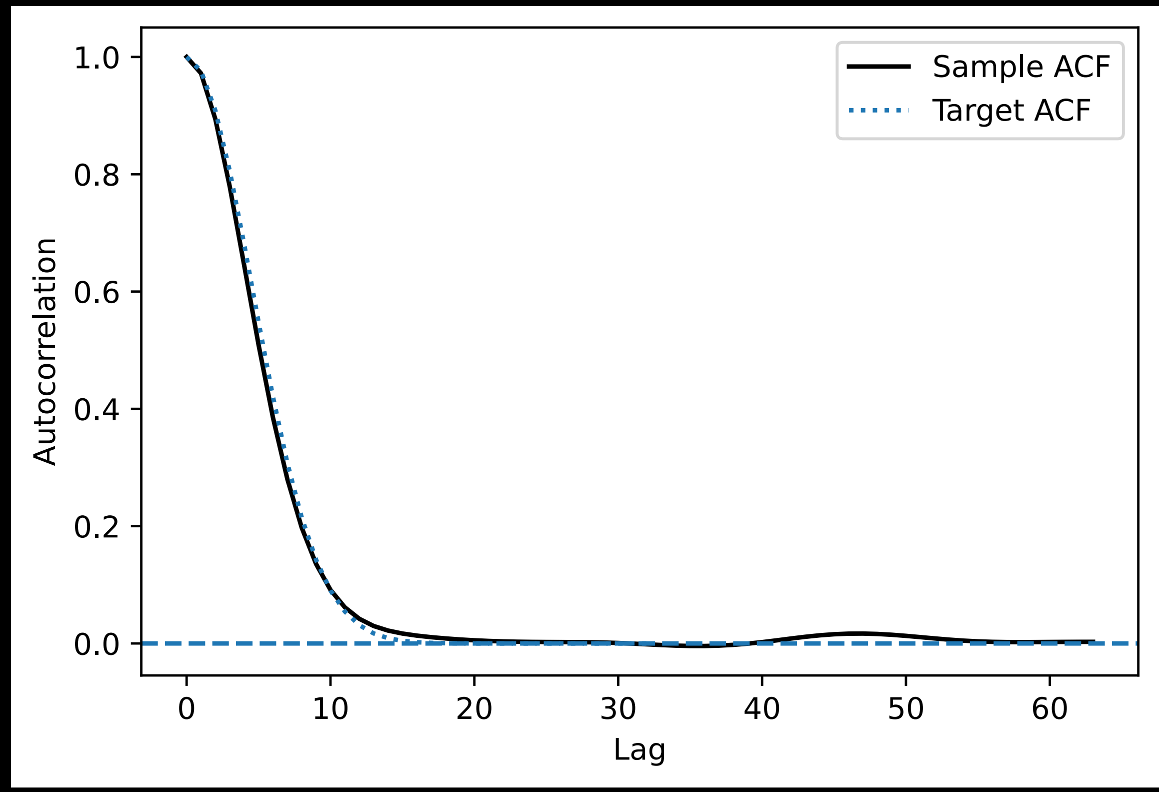
n = 1e5

$\Delta t_d = 30$ s

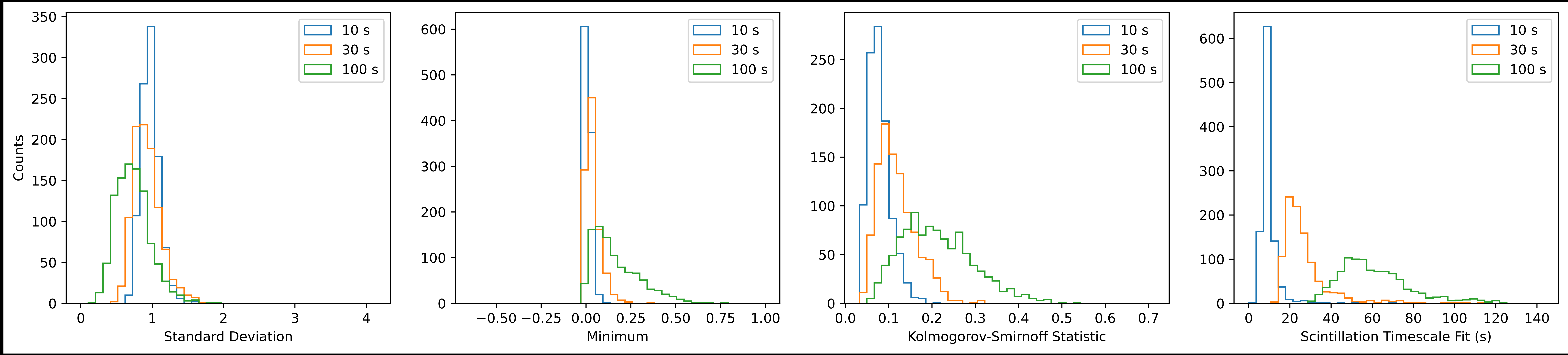
Intensity histogram



Autocorrelation



Statistics using low number of synthetic samples



Std. Dev.

Minimum

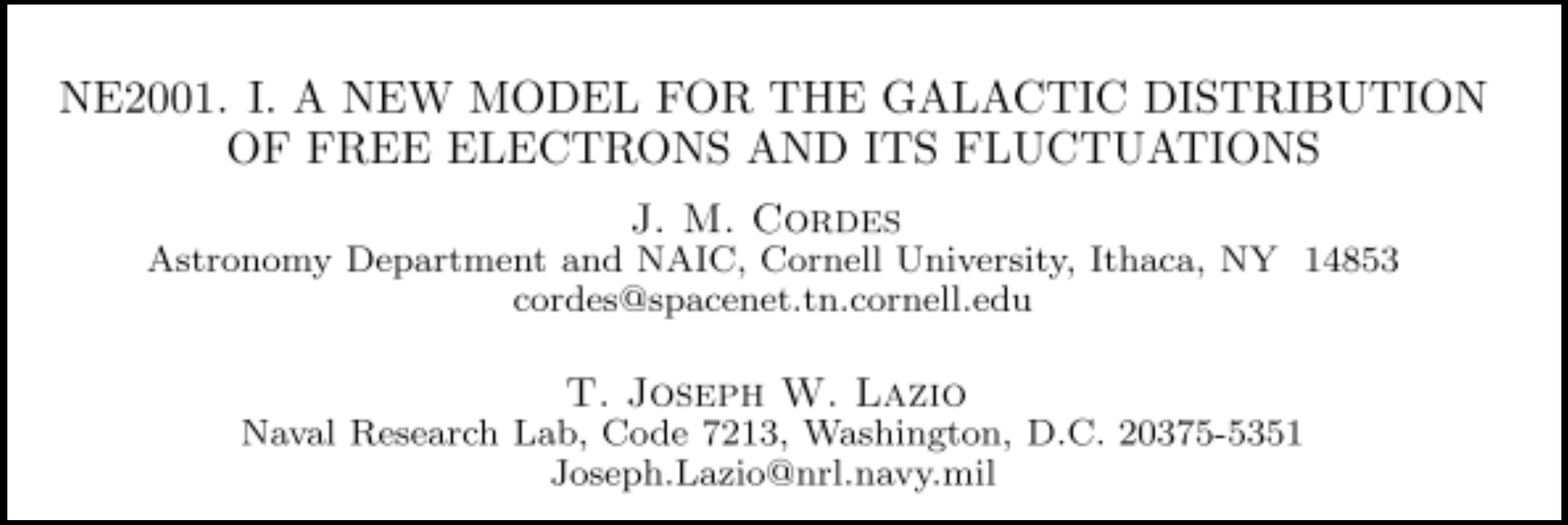
KS Statistic

Timescale Fit

10 min "observation", 4.65 s

Estimating scattering strength

- NE2001 model estimates scattering parameters



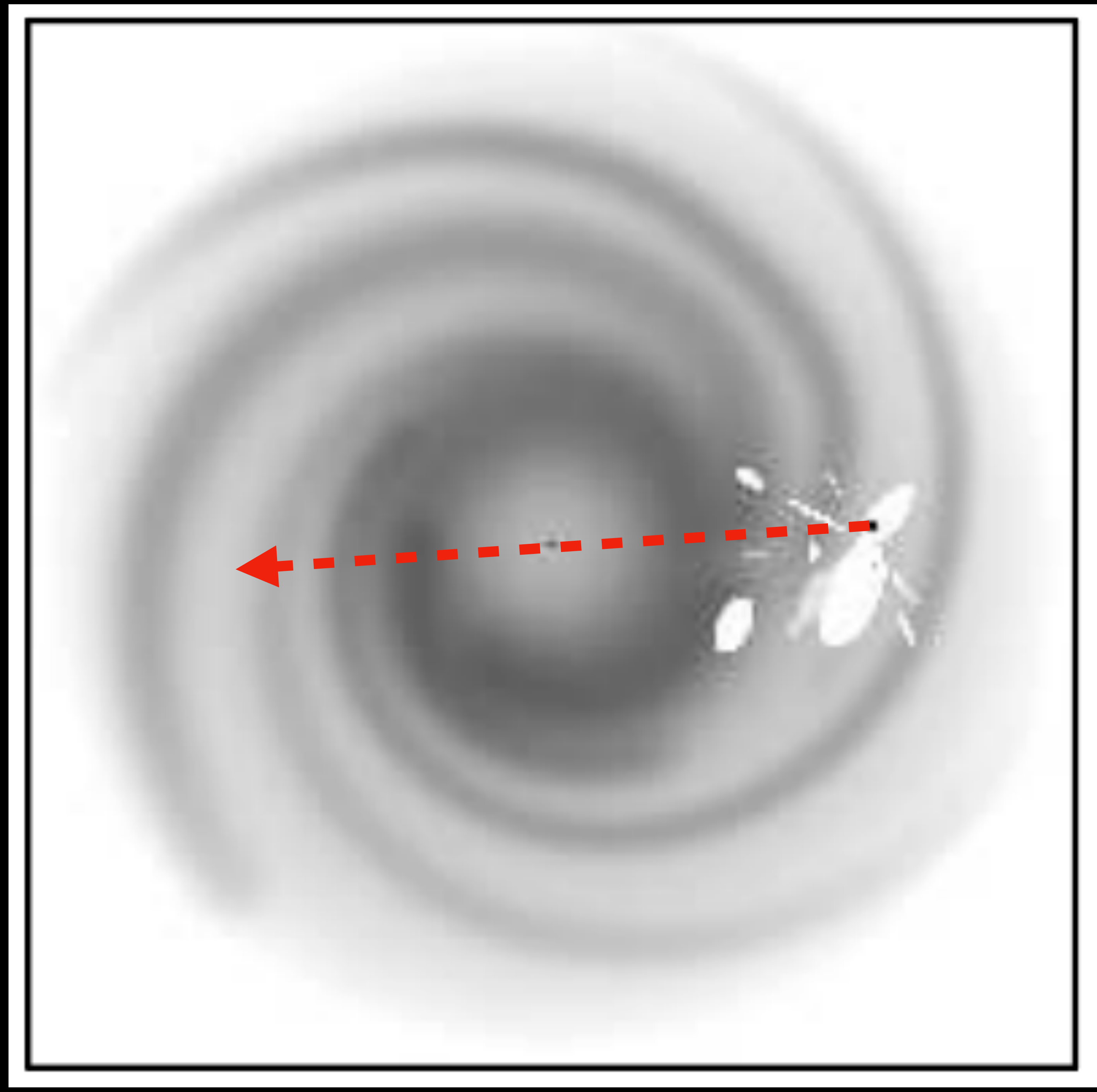
NE2001. I. A NEW MODEL FOR THE GALACTIC DISTRIBUTION OF FREE ELECTRONS AND ITS FLUCTUATIONS

J. M. Cordes
Astronomy Department and NAIC, Cornell University, Ithaca, NY 14853
cordes@spacenet.tn.cornell.edu

T. Joseph W. Lazio
Naval Research Lab, Code 7213, Washington, D.C. 20375-5351
Joseph.Lazio@nrl.navy.mil

- Assumes defaults of 1 GHz and 100 km/s – requires scaling!

$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$



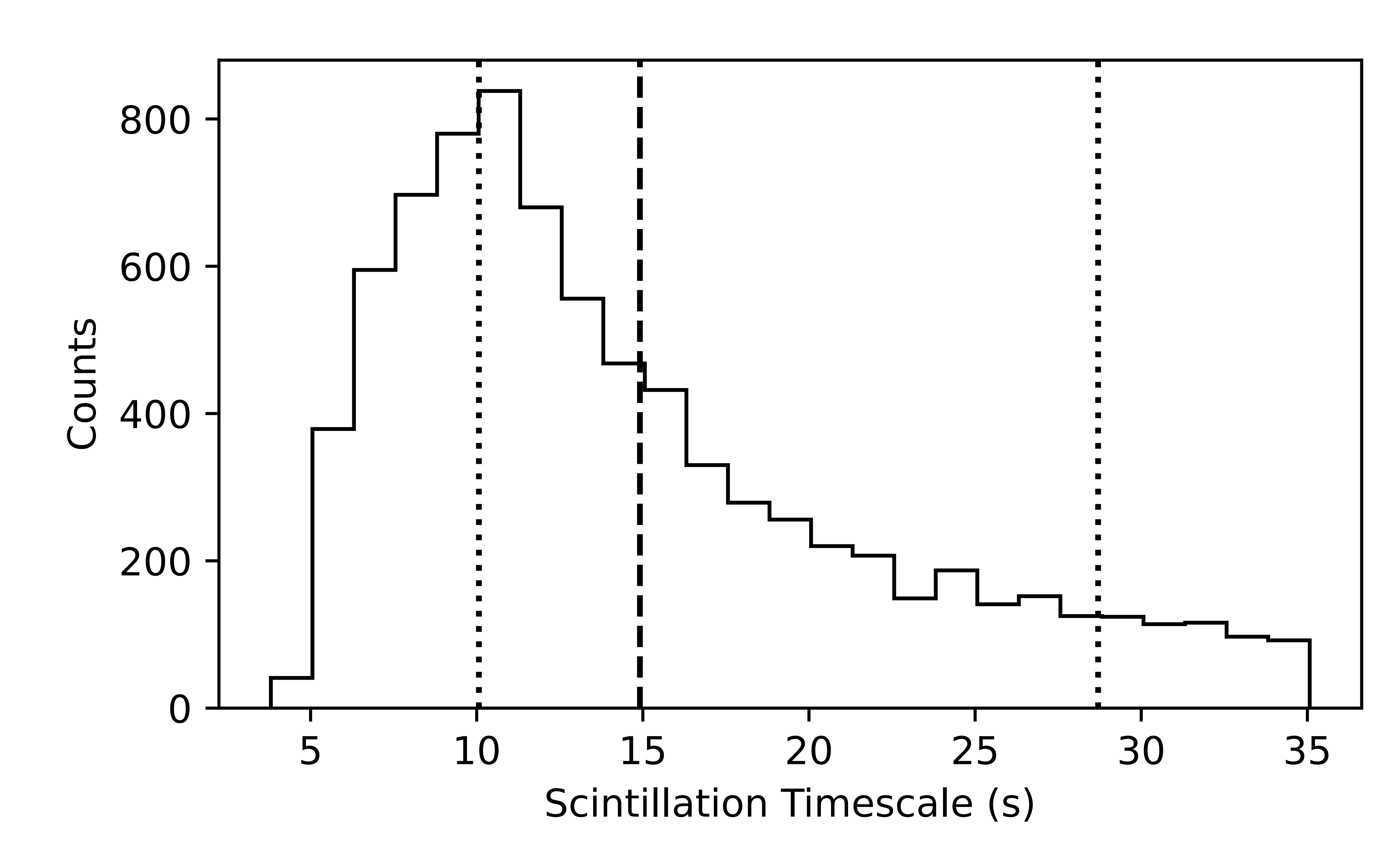
- We use Monte Carlo sampling for unknown parameters

C-band

(l, b) = (1, 0)

Inter-quartile

Media

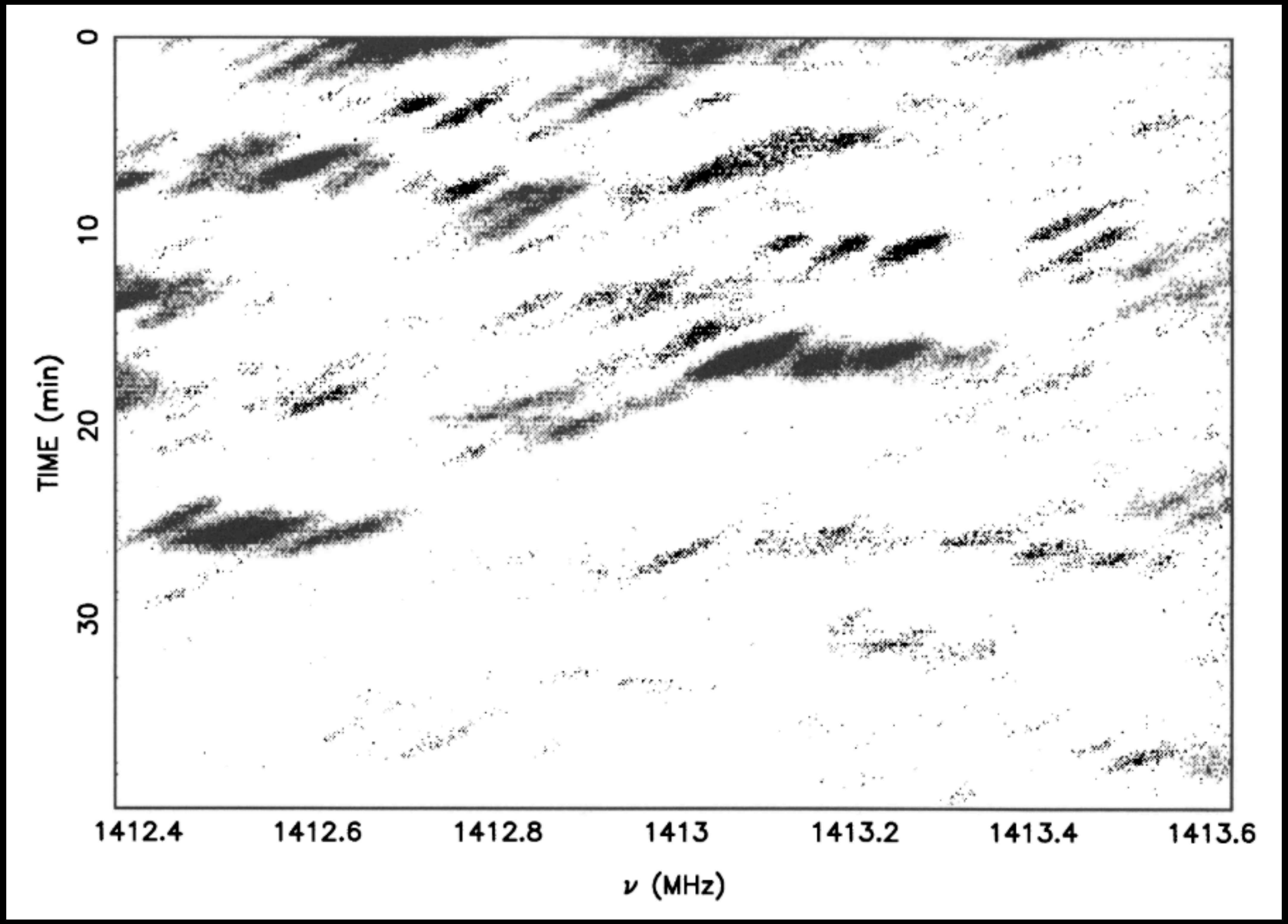


ISM Scattering & Scintillation

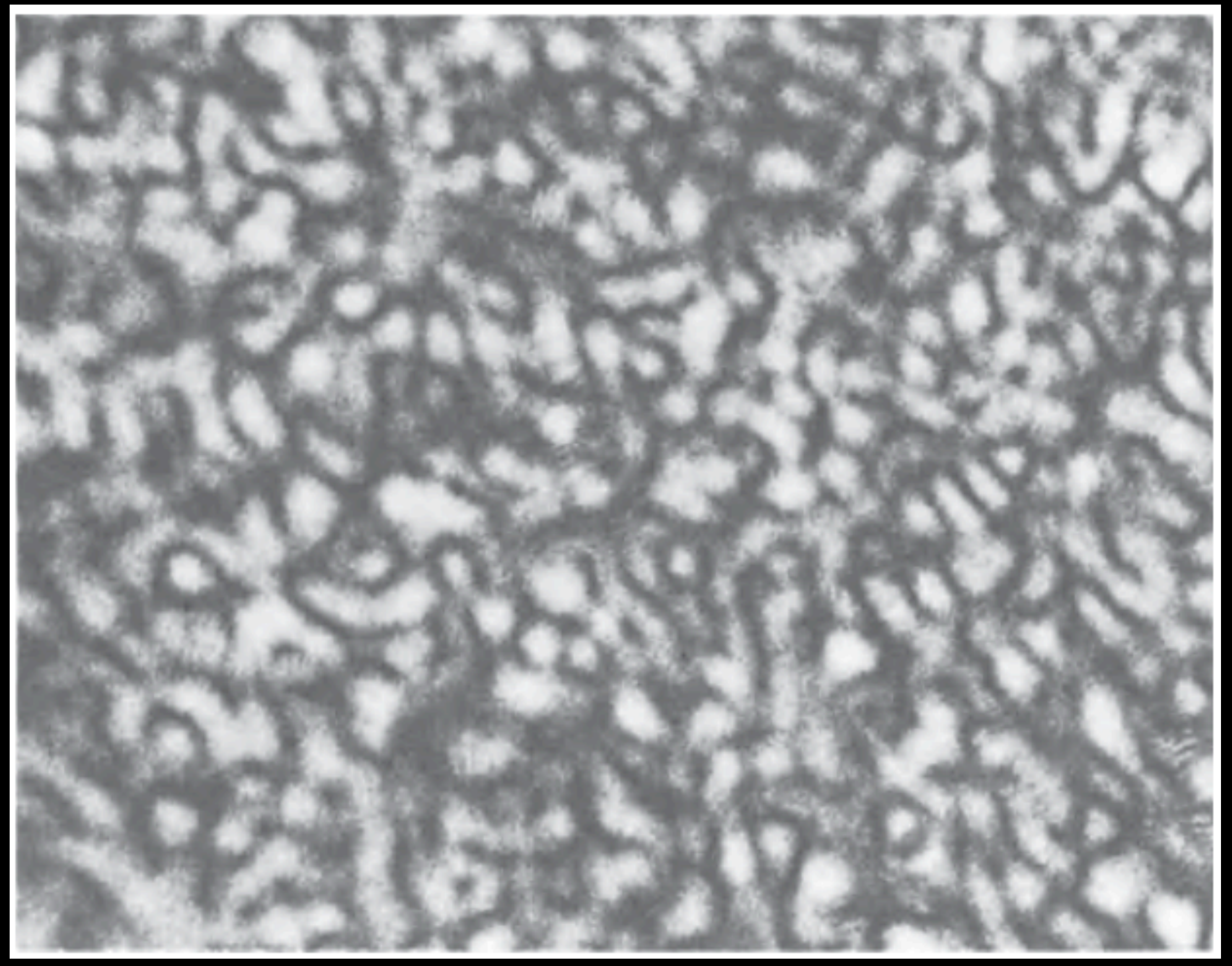
- Interaction between radio waves and free electrons in plasma

- Pulsar observations paved the way

- Parallels with laser speckle



Cordes & Lazio 1991



Goodman 1984

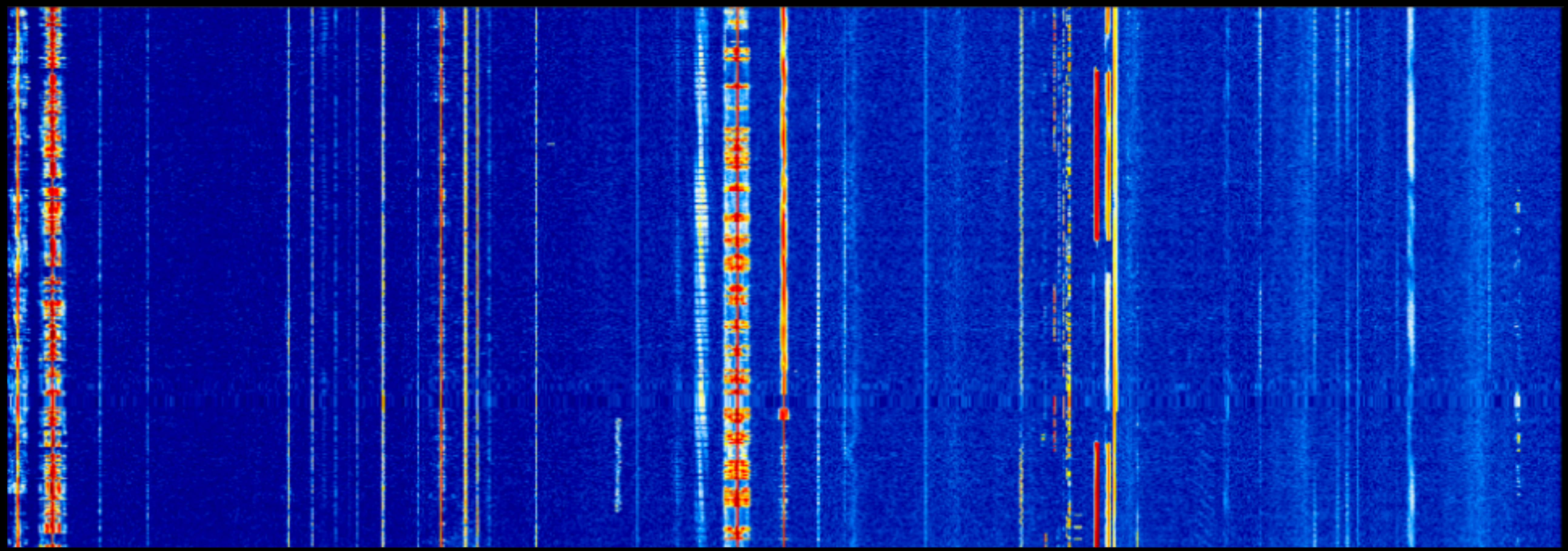
Scattering and SETI research

INTERSTELLAR SCATTERING EFFECTS ON THE DETECTION OF NARROW-BAND SIGNALS

James M. Cordes and T. Joseph Lazio
National Astronomy and Ionosphere Center and Department of Astronomy, Cornell University, Ithaca, NY 14853

Received 1990 October 4; accepted 1991 January 15

- Many studies acknowledge scattering but attempt to avoid it
- Generally, SETI techniques aren't sensitive to detailed morphology
    - Noise, modulation, S/N
- Stochastic effects are hard to describe



Bigger picture: research goals

- Where and how should we look to target scintillated narrowband sources? Is this feasible and worth trying?

- Develop a overall methodology, coding, and analysis framework

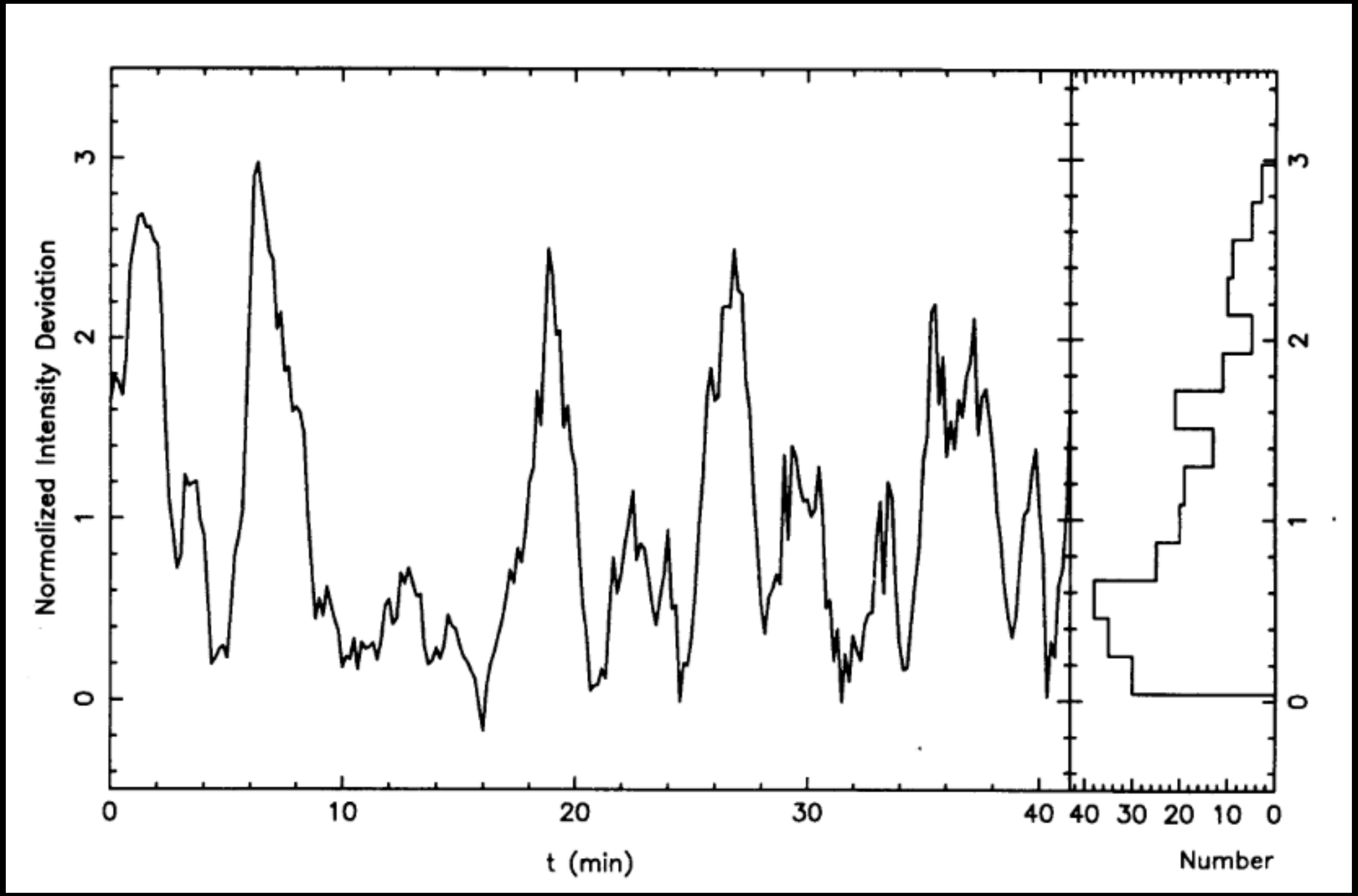
Can we detect scintillated narrowband technosignatures?

1. What scintillation timescales should we expect?
2. How can we probe asymptotic statistics?
3. Can we differentiate scintillated signals from existing RFI?

What would strongly scintillated signals look like?

Assuming 100% duty-cycle narrowband emission

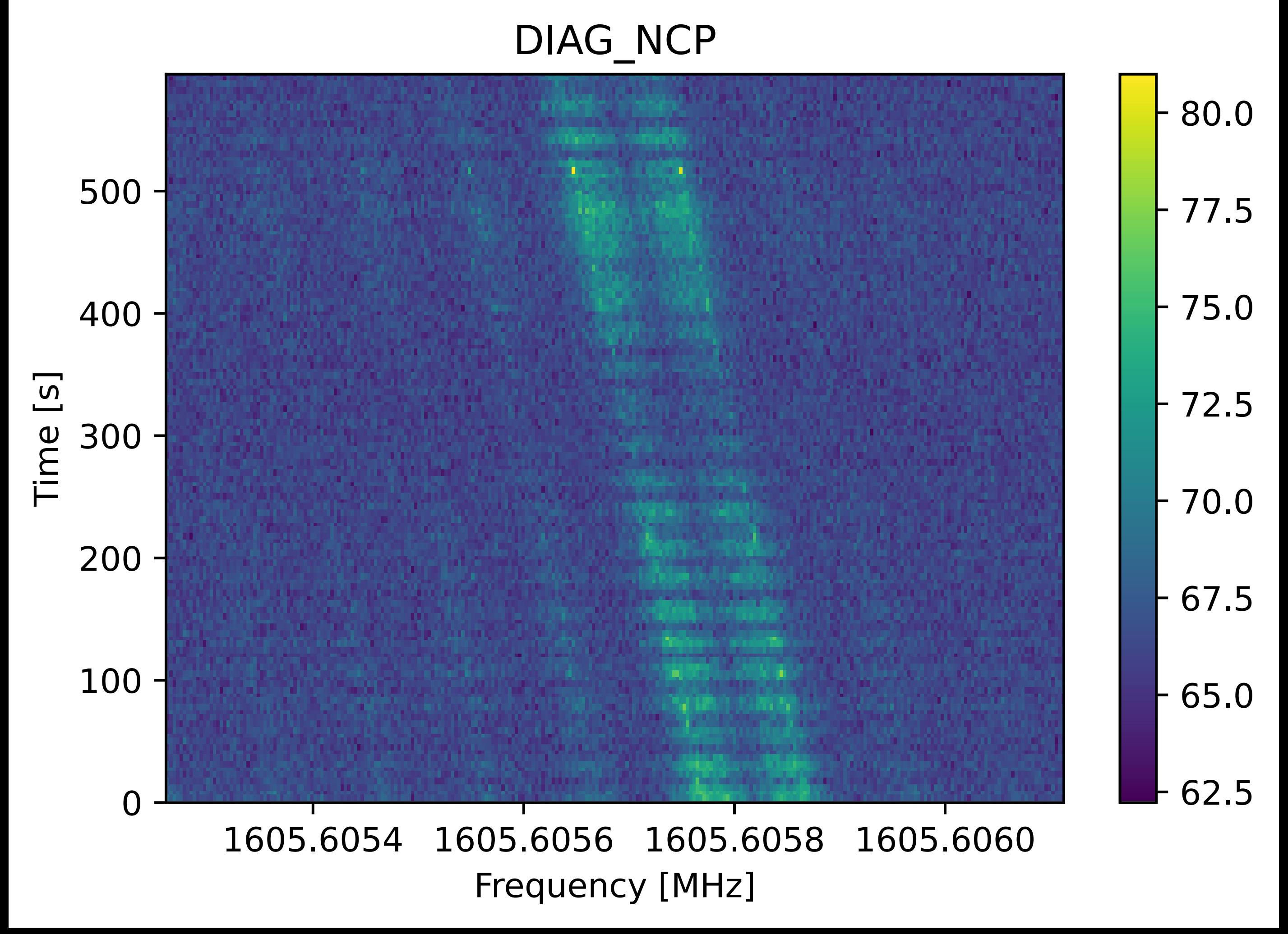
- Asymptotic behavior:
  - Exponential intensity distribution
  - Approximately Gaussian autocorrelation, with characteristic timescale

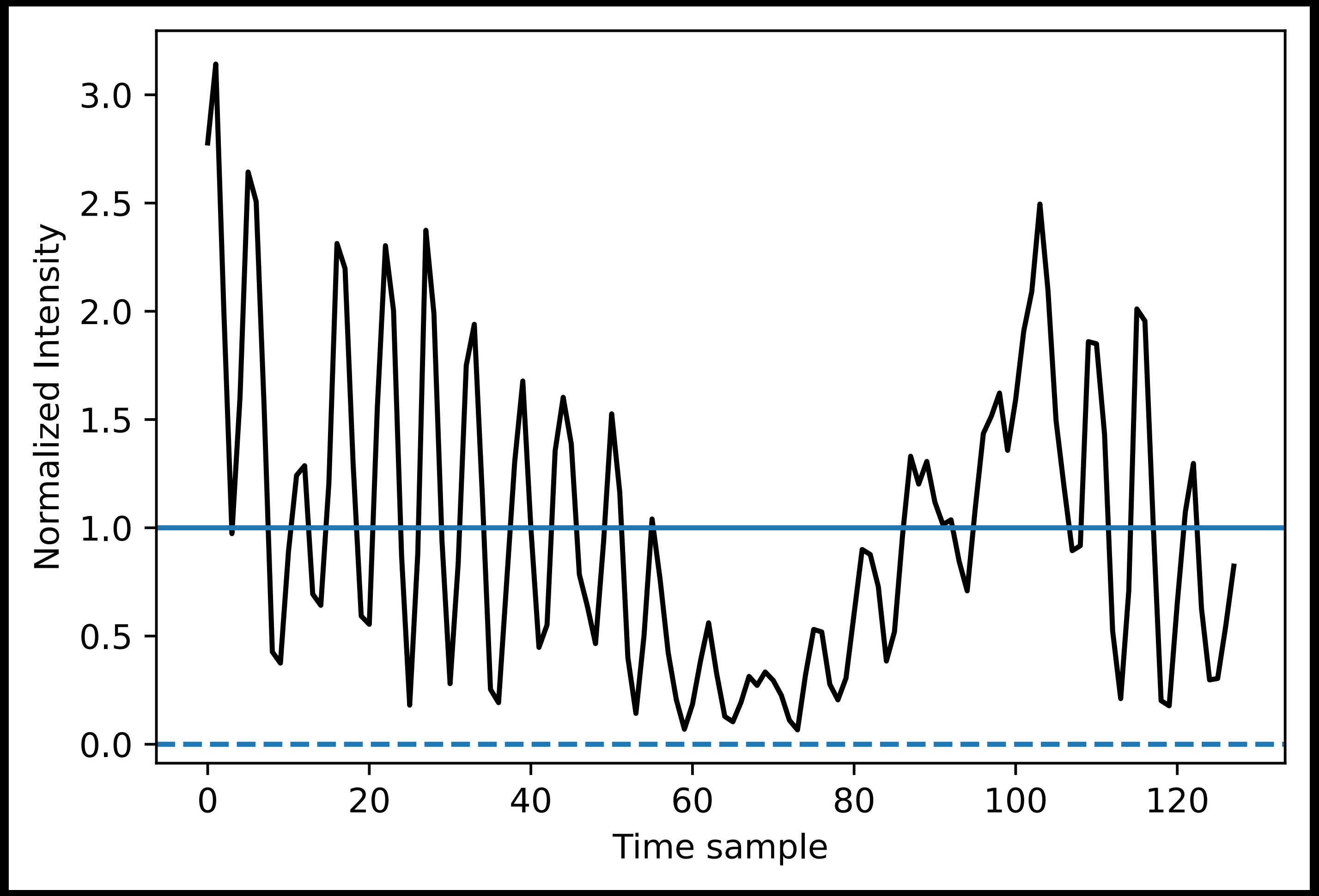


Cordes & Lazio 1991;
Cordes, Lazio, Sagan 1997

Given a signal... is it scintillated?

- Create bounding box around narrowband signal
- Estimate noise-subtracted intensity time series, normalized to mean 1
- Compute "diagnostic statistics" that pertain to asymptotic behavior
  - E.g. standard deviation, Kolmogorov-Smirnoff statistic, fit to autocorrelation function





What would strongly scintillated signals look like?

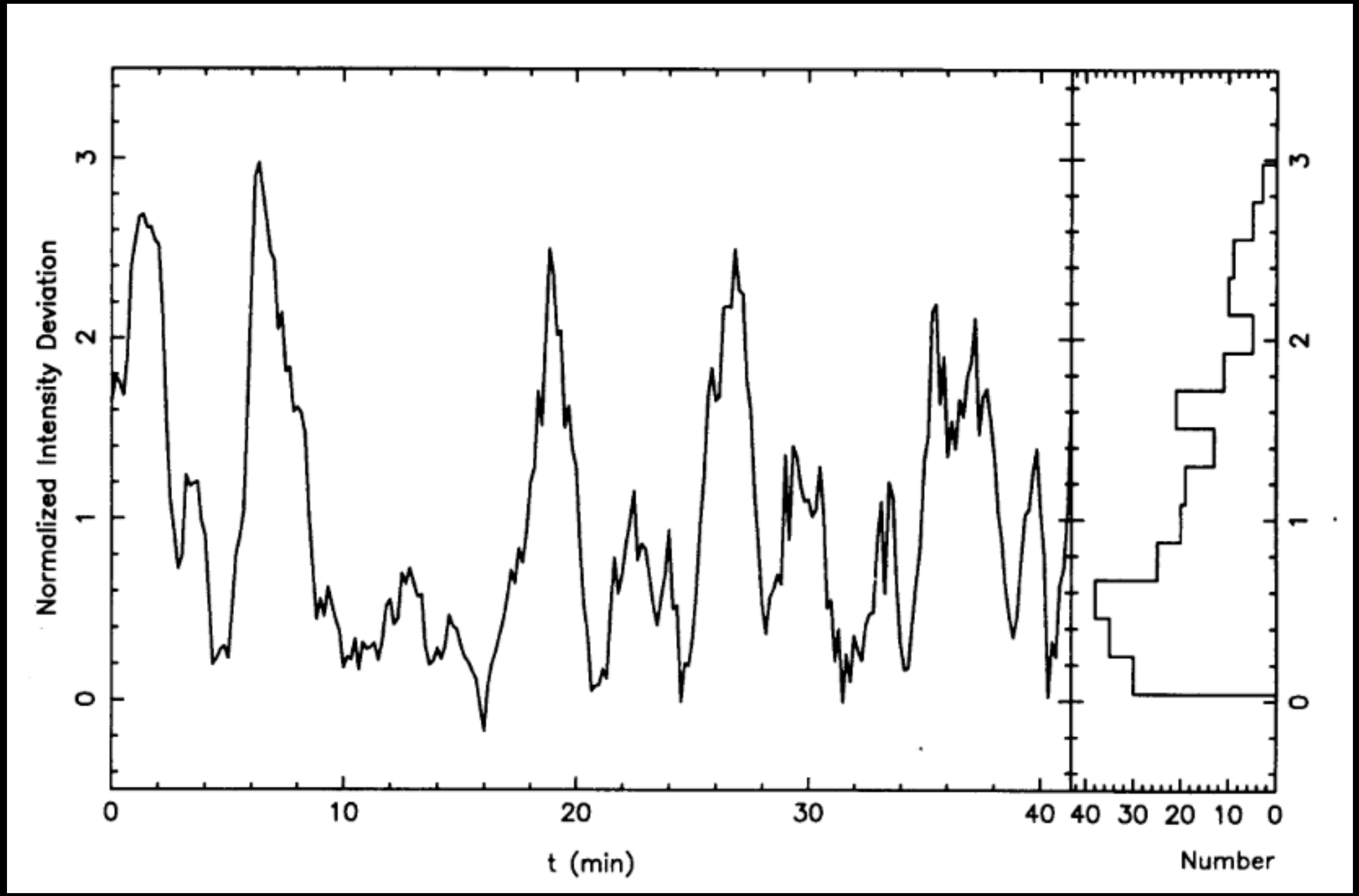
Assuming 100% duty-cycle narrowband emission

- Expected asymptotic behavior:
- Exponential intensity distribution

$$p(I) \propto e^{-I/\langle I \rangle}$$

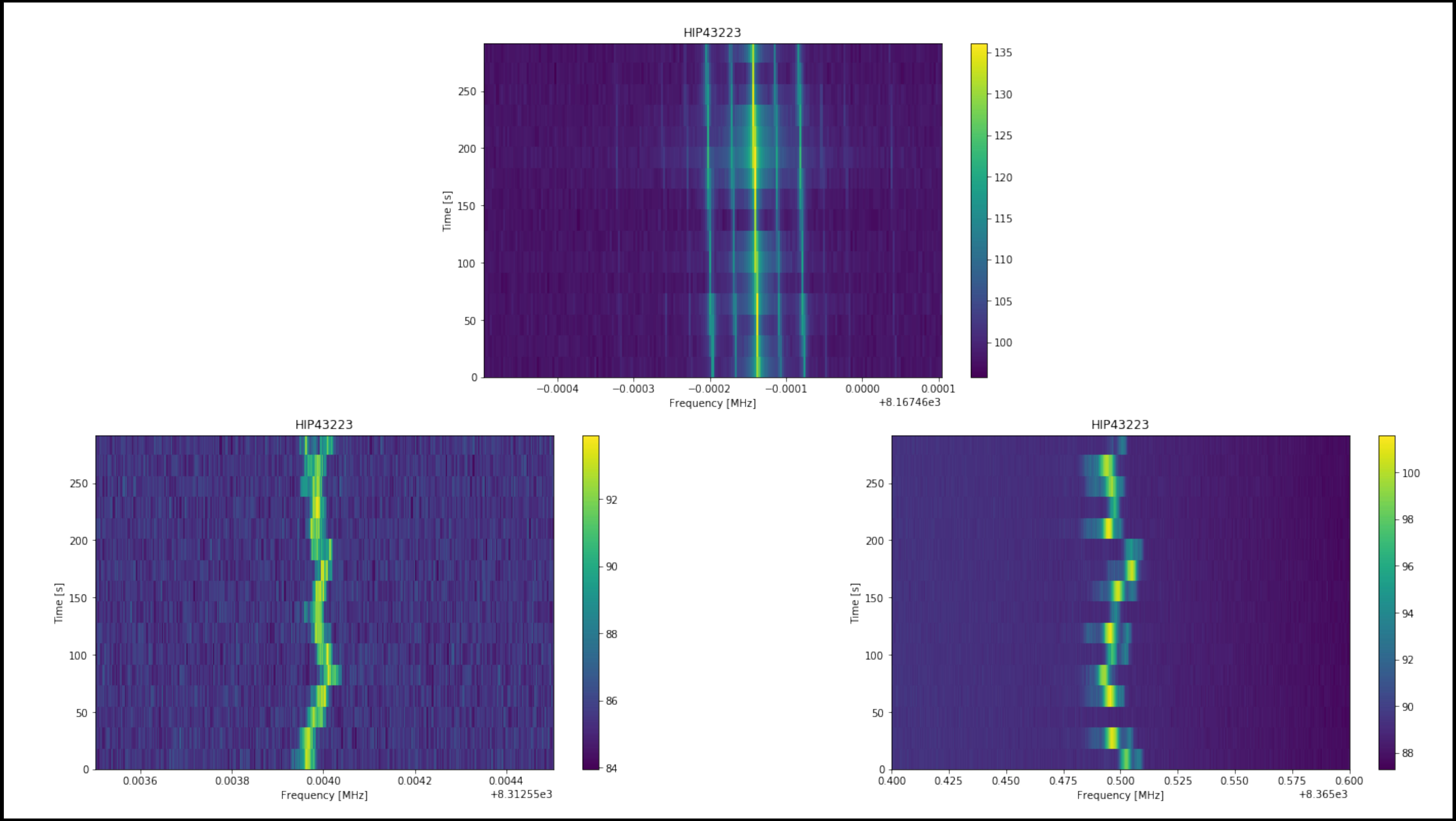
- Near Gaussian autocorrelation, with characteristic timescale

$$\rho(\tau) \sim e^{-(\tau/\Delta t_d)^2}$$



Cordes & Lazio 1991;
Cordes, Lazio, Sagan 1997

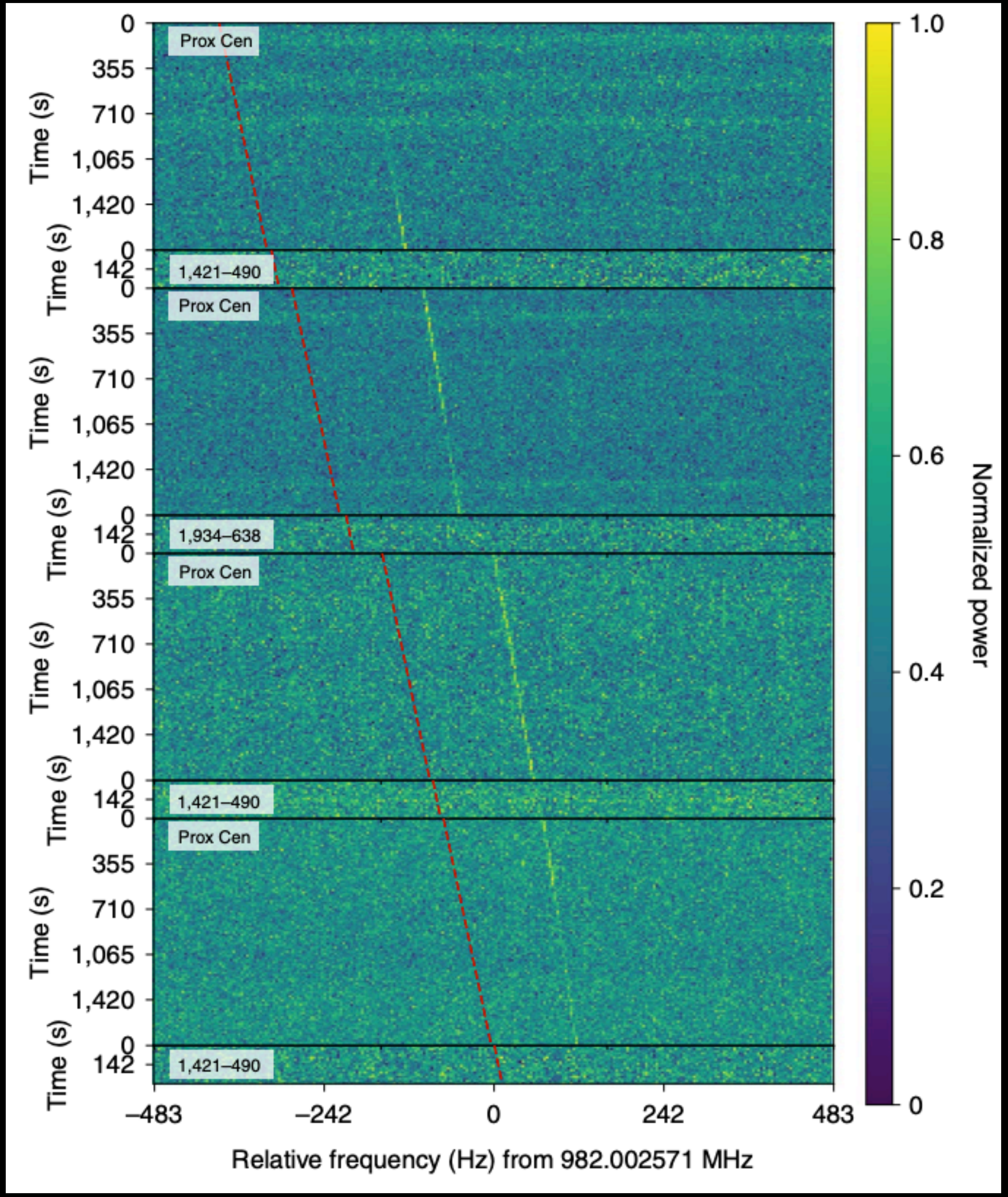
But what does the RFI environment look like?



Extra Slides x2

Plasma effects as a search filter for SETI

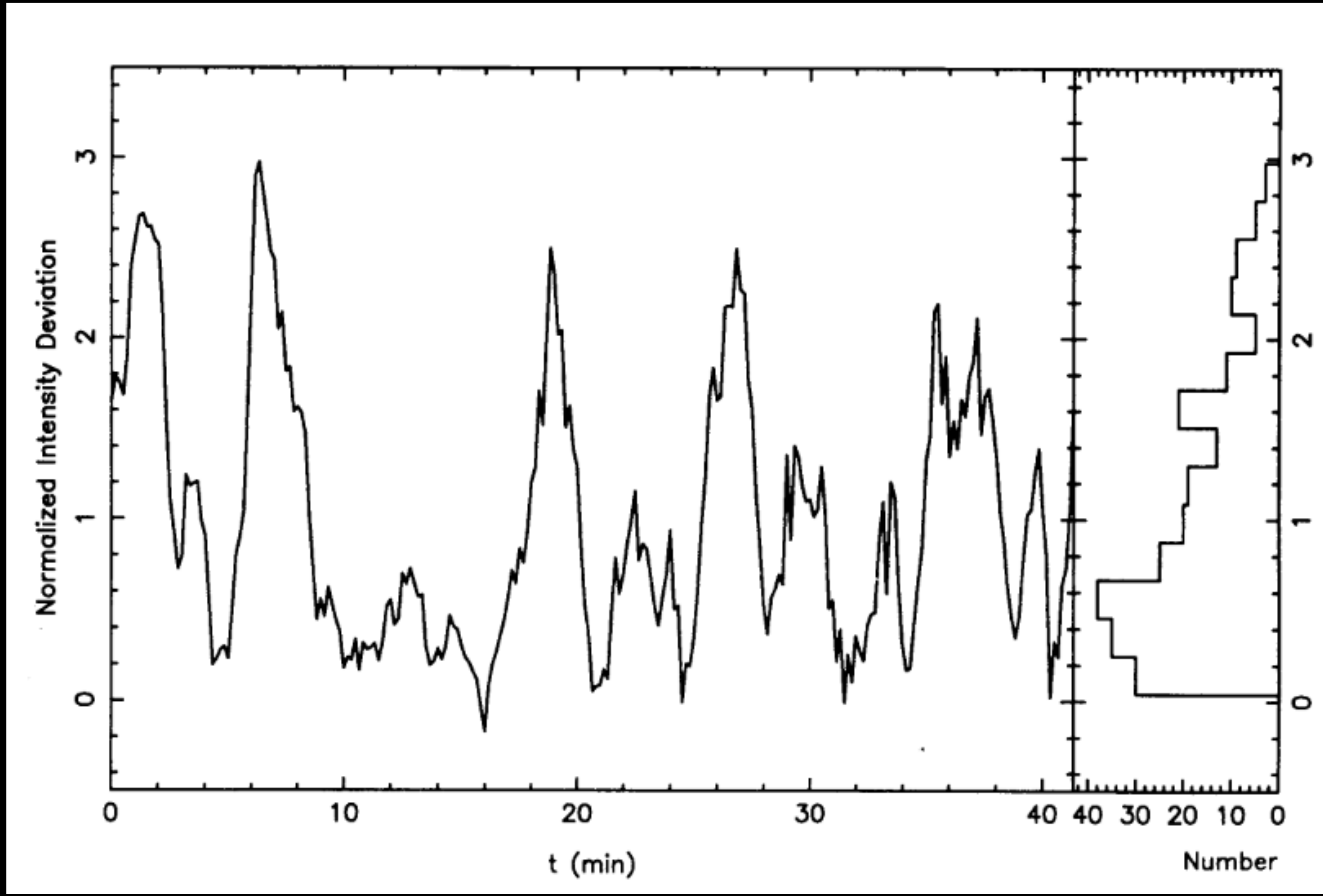
- Modern radio SETI involves detecting a vast number of signals and filtering likely candidates
- For a few reasons, most filters do not involve the effects on the signal itself
- We propose that in some cases, we can detect scintillation from the ISM in narrowband signals, which would heavily imply extrasolar origin



Smith et al. 2021

Methods

- Target 100% duty-cycle, narrowband transmitters
- Since scintillation is stochastic by definition, identify measurable statistics
- Estimate intensity time series from detected signals for analysis
- Use procedure on RFI in unlikely directions to probe the interference environment



Cordes & Lazio 1991;
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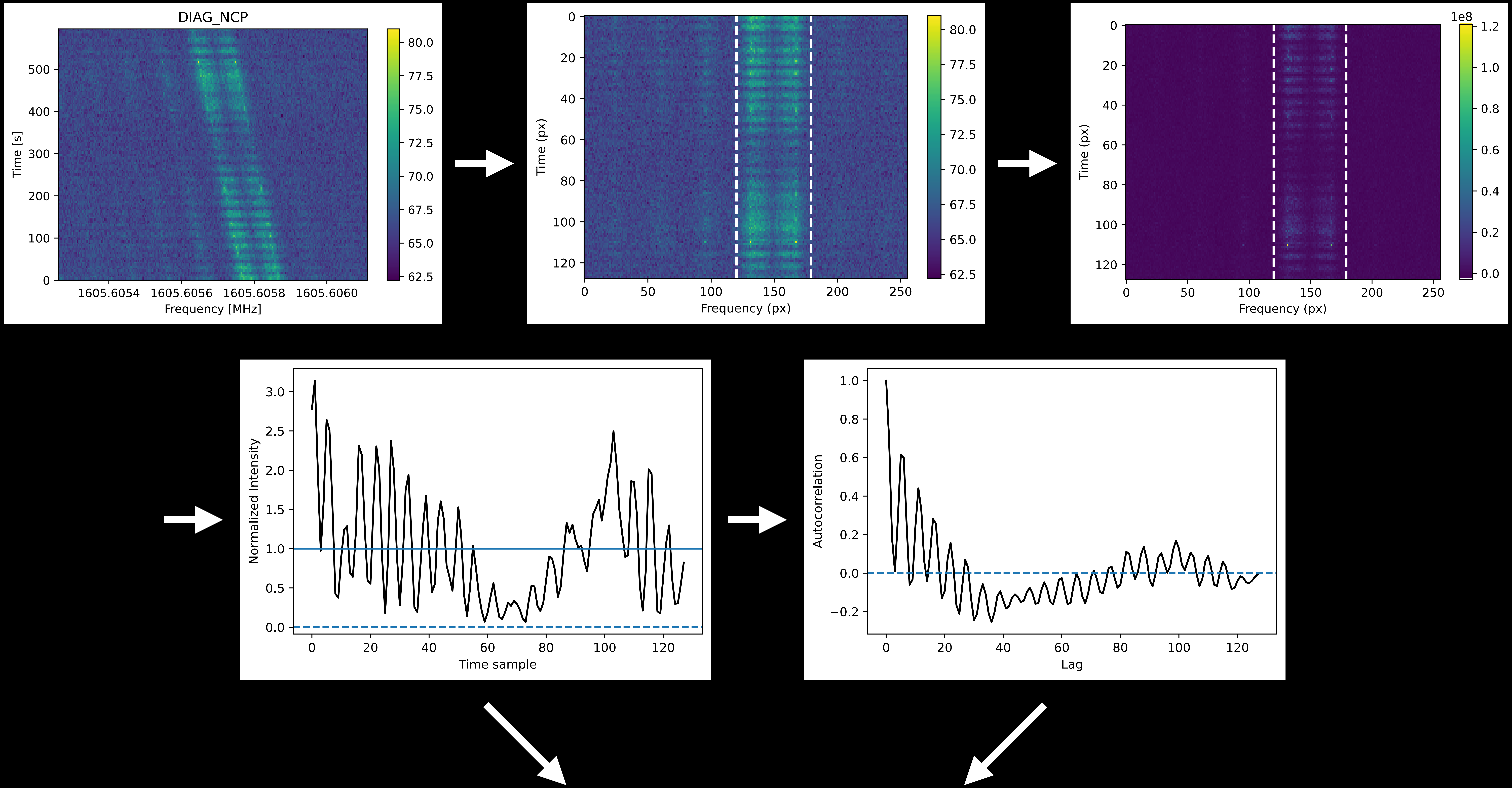
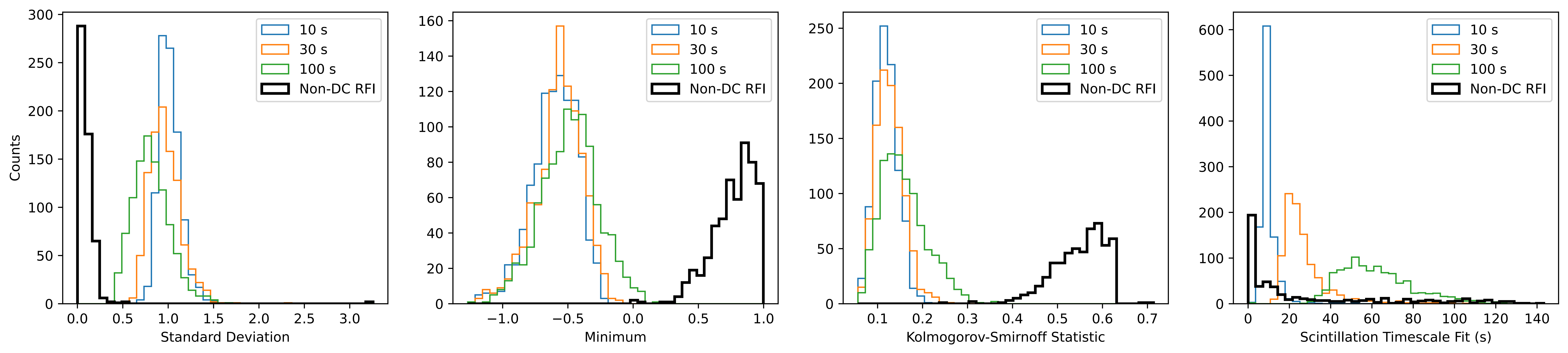


Diagnostic statistics

RFI Analysis

C band

S/N = 25



Standard Deviation

Minimum

Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

RFI Analysis

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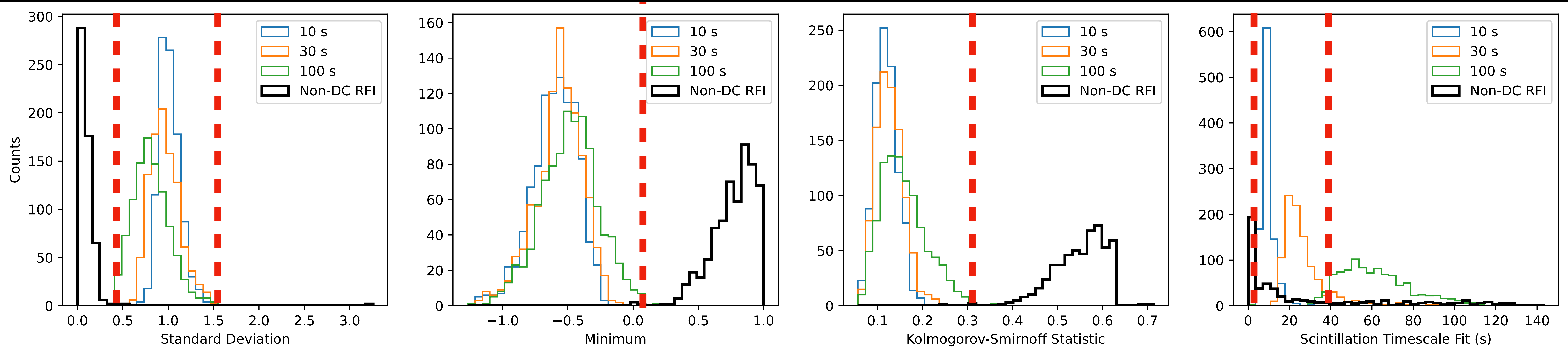


Standard Deviation

Minimum

Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

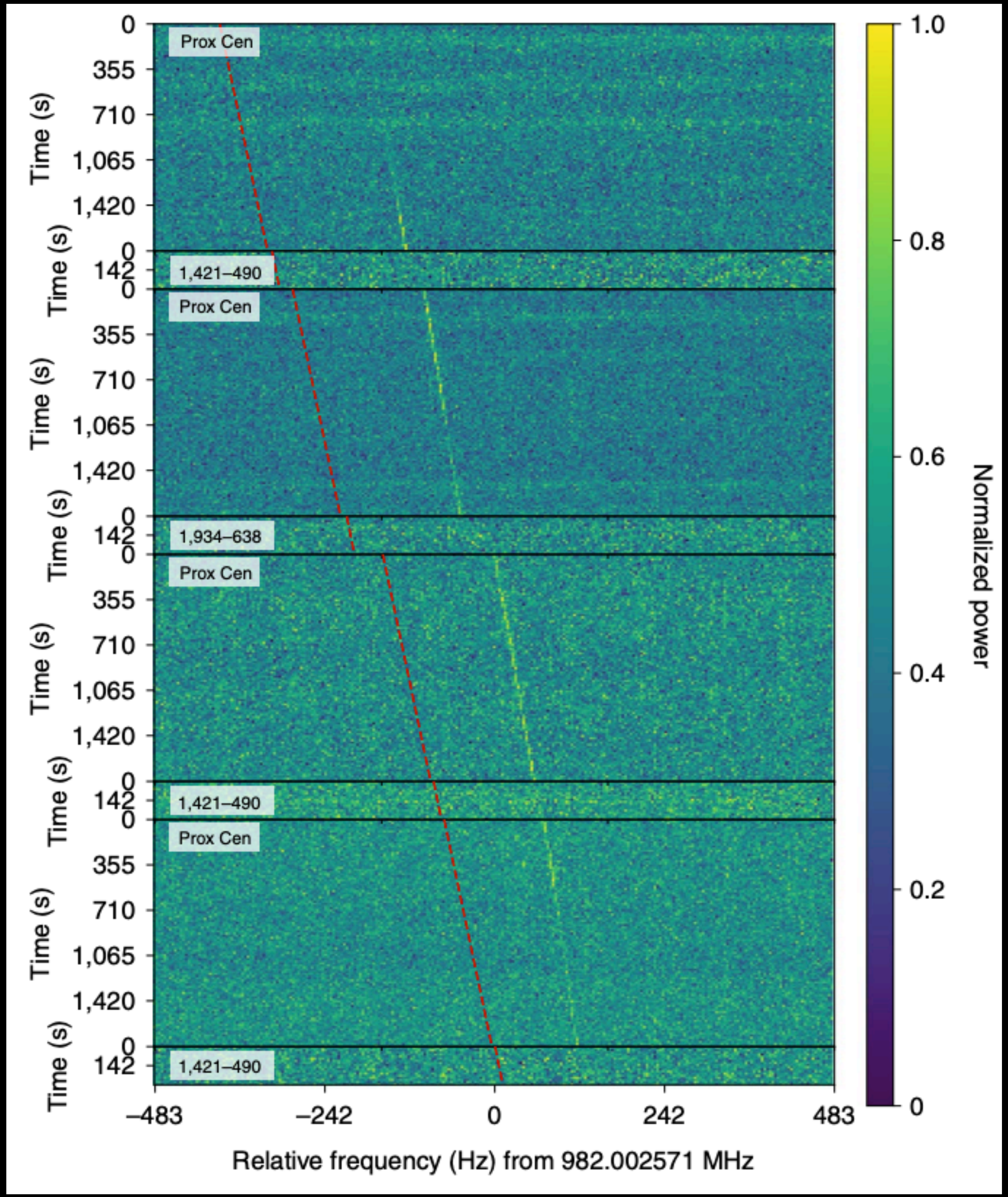
Summary

- Developed a framework for scintillation analysis, with accompanying code
- Because of RFI environment, higher frequencies are more amenable
- Looking forward: dedicated survey with custom resolution to search near the Galactic Center
- Better extraction / classification methods may lead to improvements

Extra Slides

Candidate identification and differentation

- Narrowband (vs. astrophysical sources)
- Non-zero drift rate (vs. RFI)
- Sky localization (vs. RFI)



Smith et al. 2021

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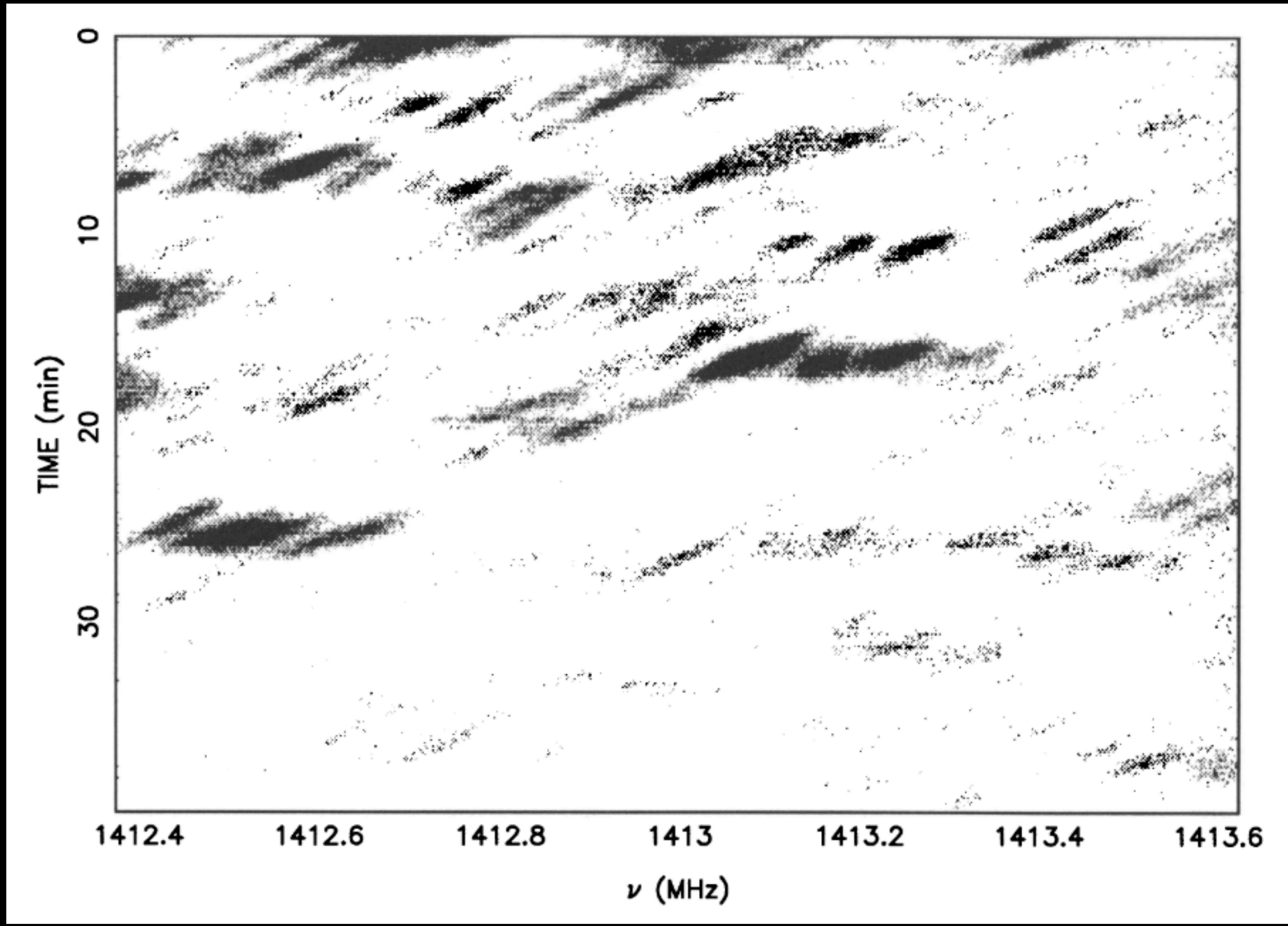
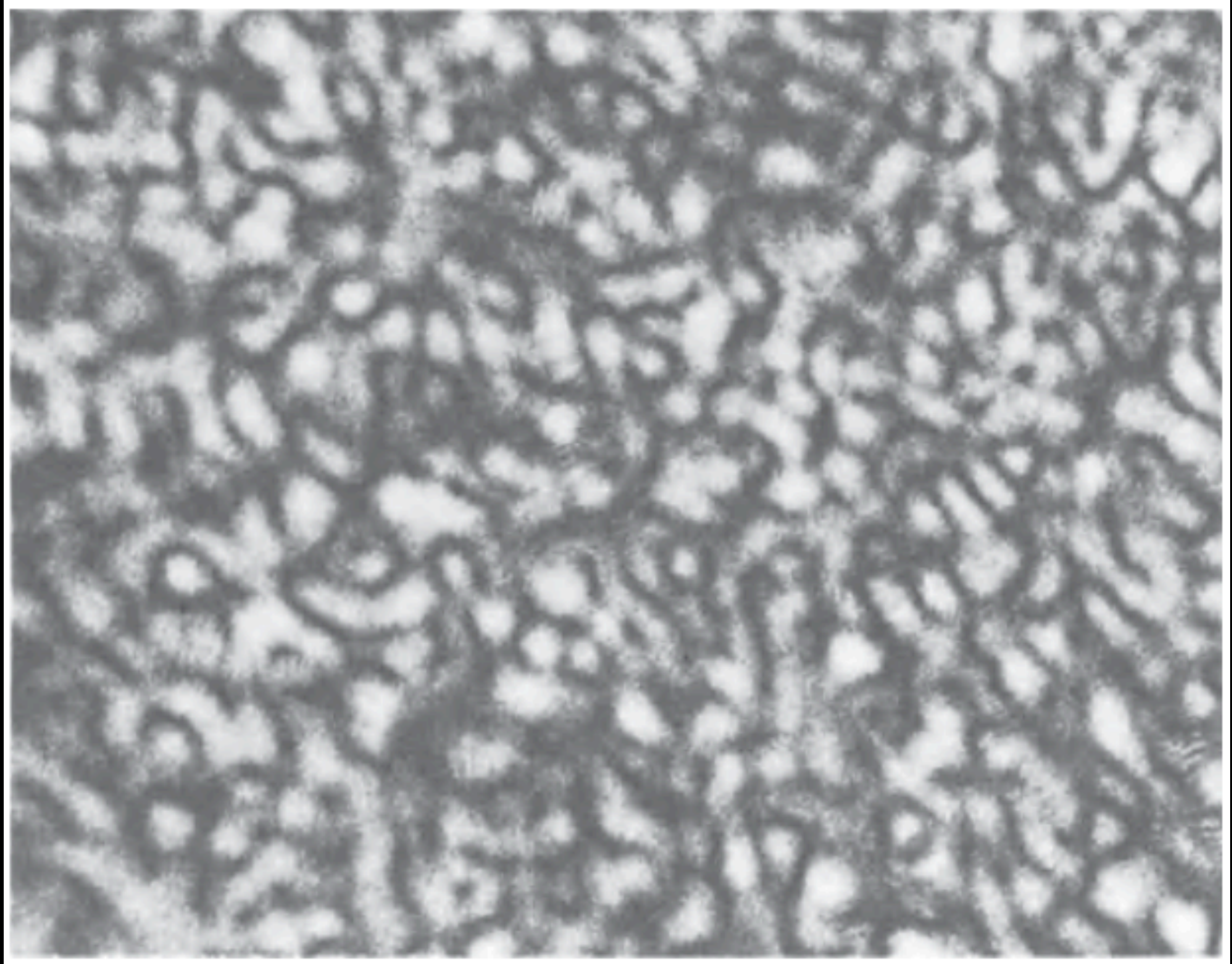


Cordes & Lazio 1991



Goodman 1984

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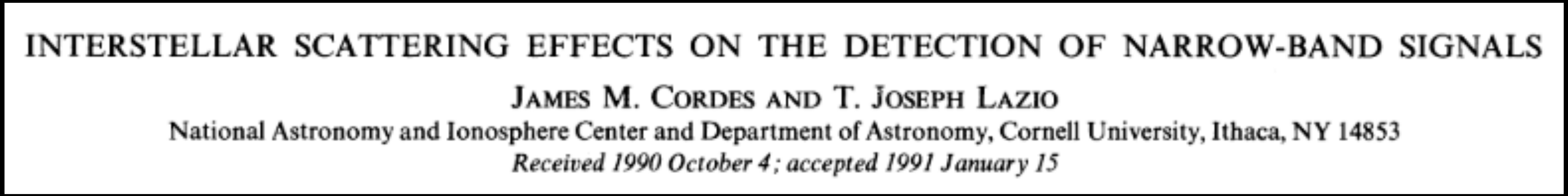

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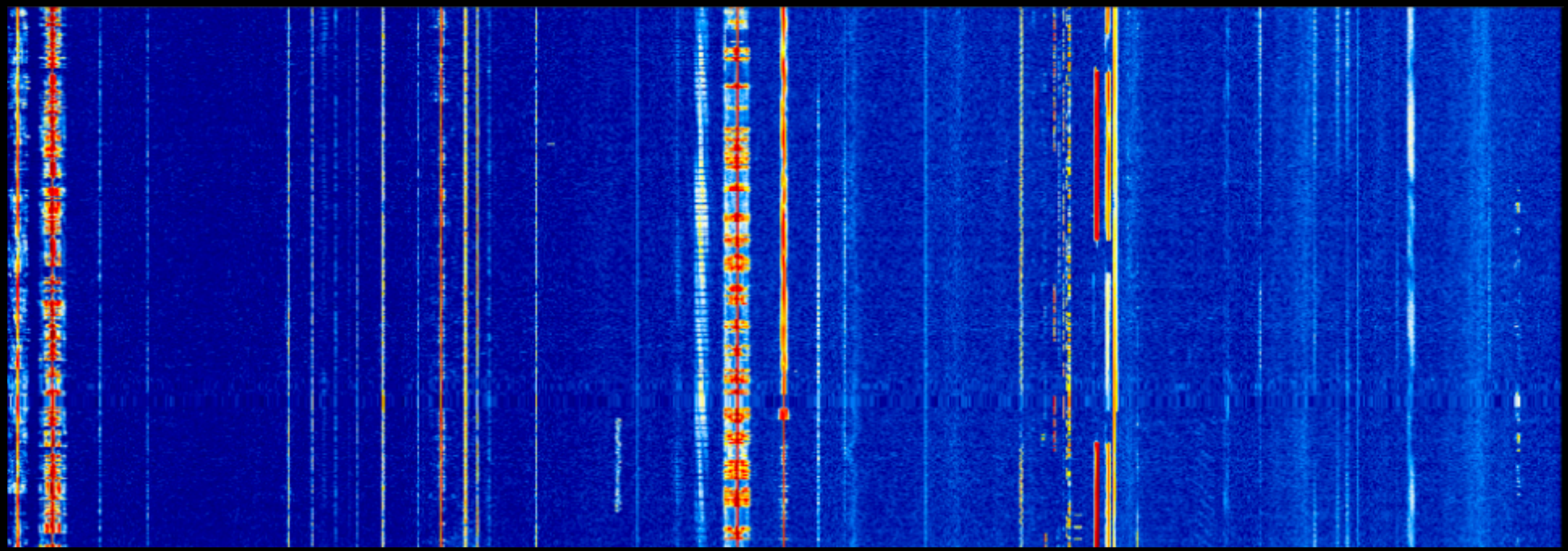

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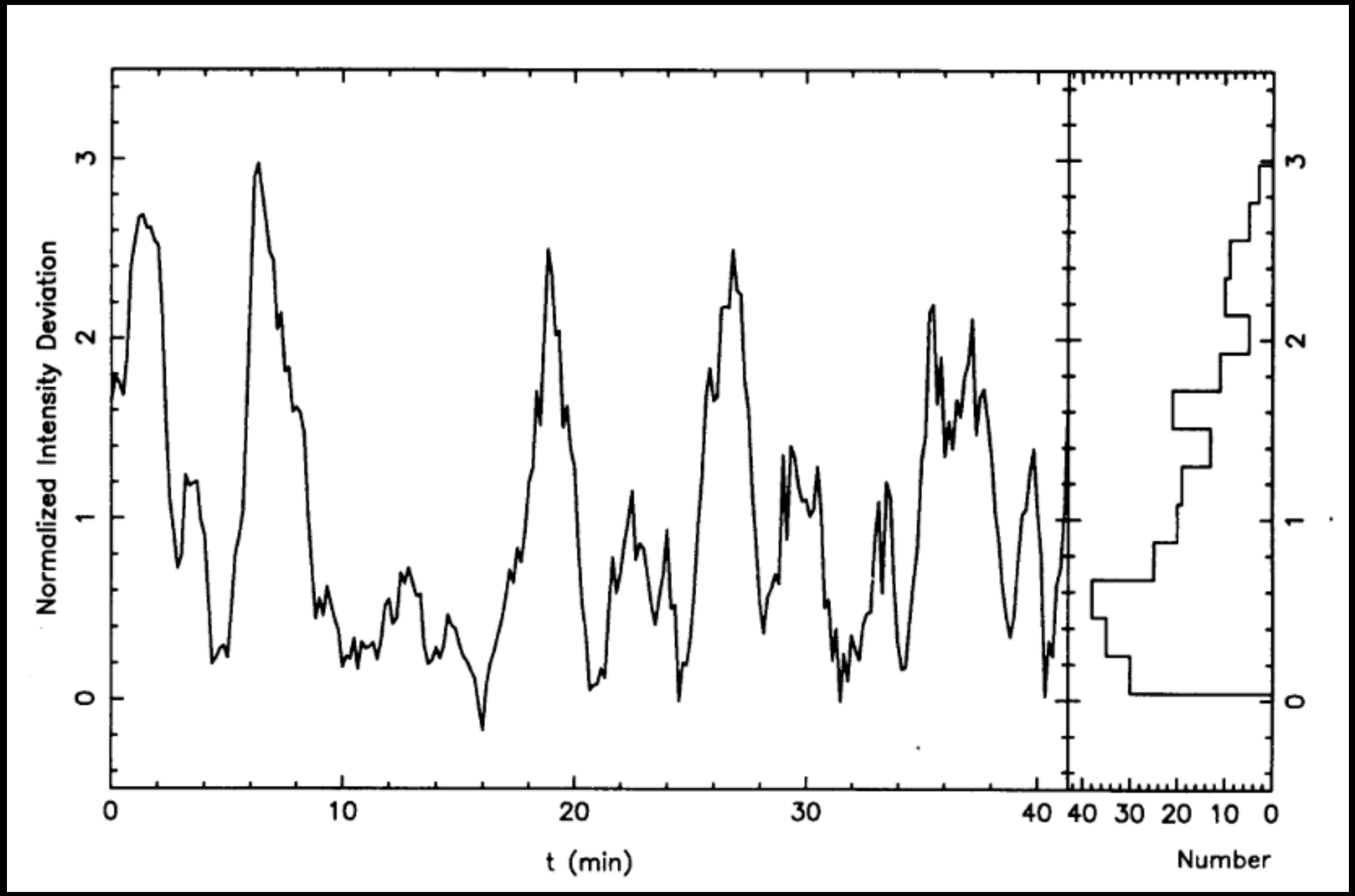

Cordes & Lazio 1991;
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- We use Monte Carlo sampling for unknown parameters

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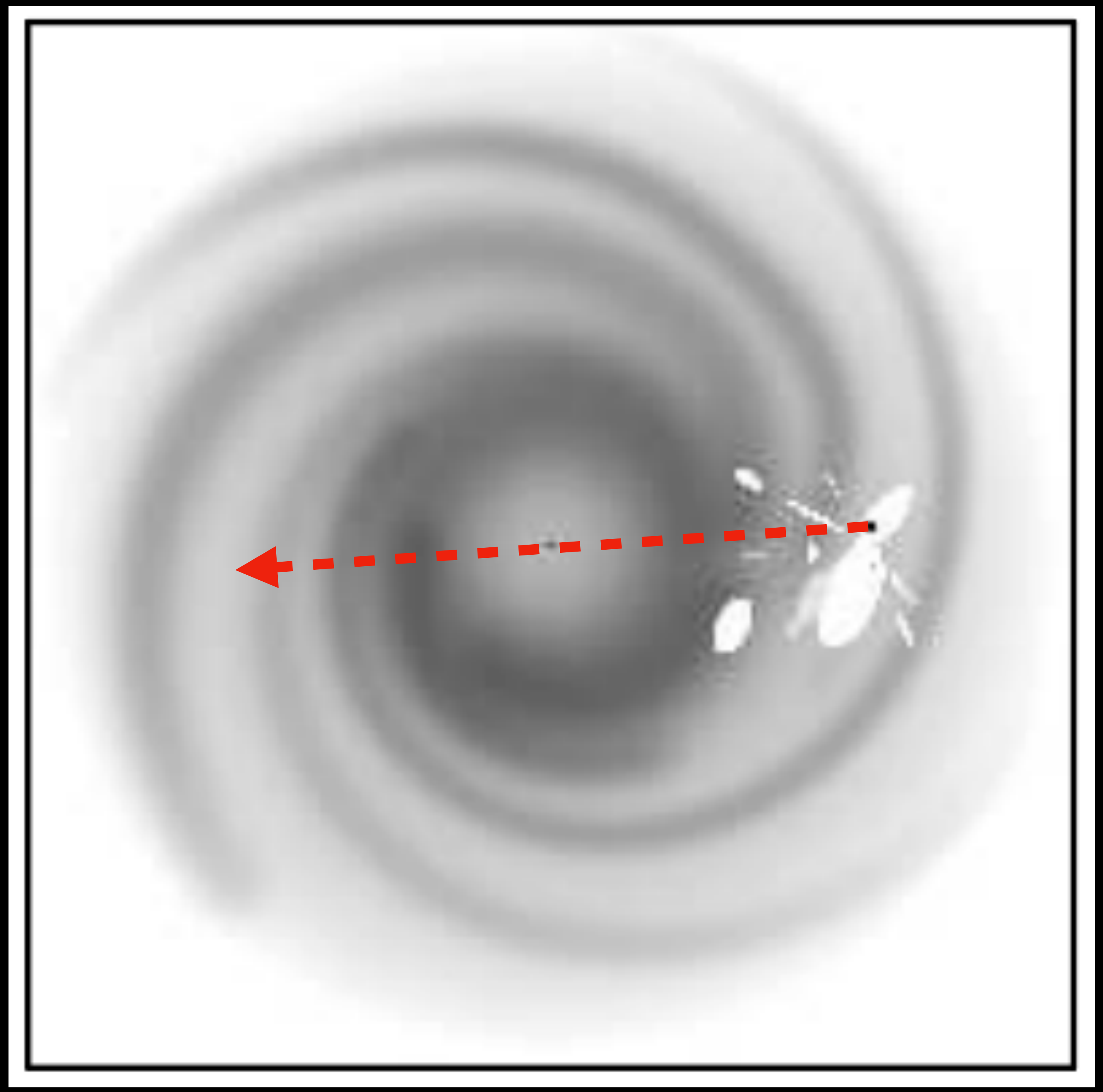
Joseph.Lazio@nrl.navy.mil

$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$

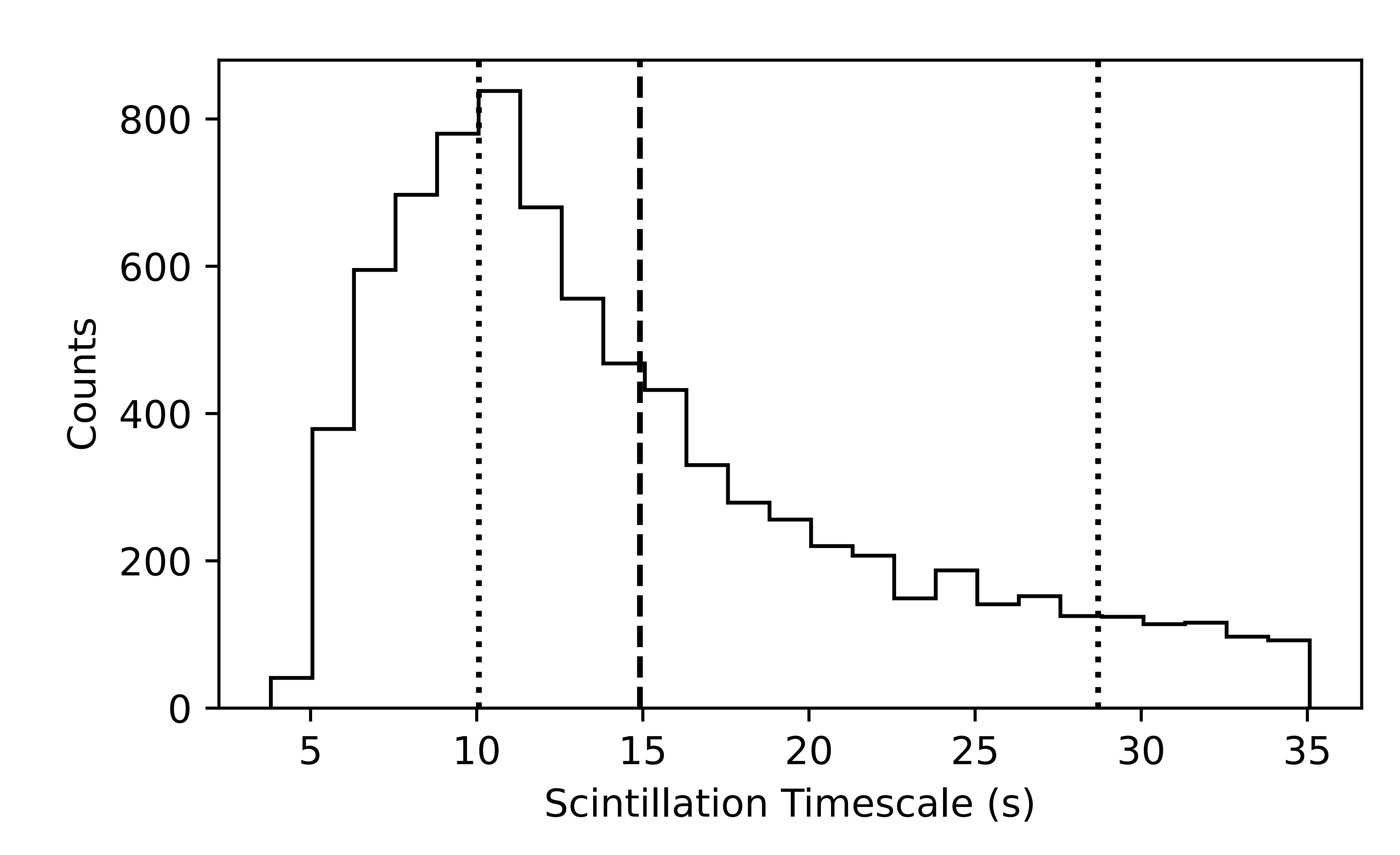


C-band

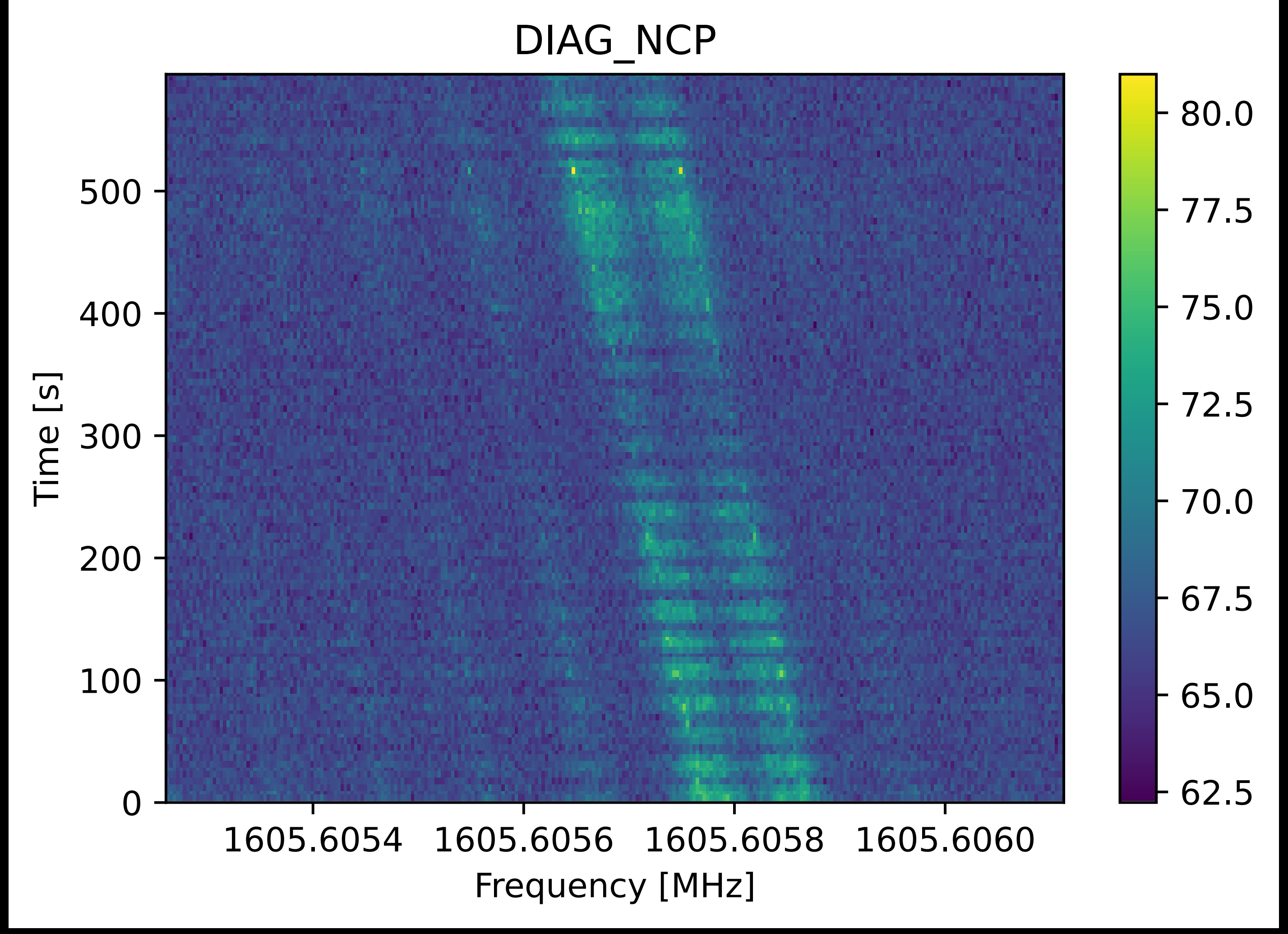
(l, b) = (1, 0)

Inter-quartile

Media

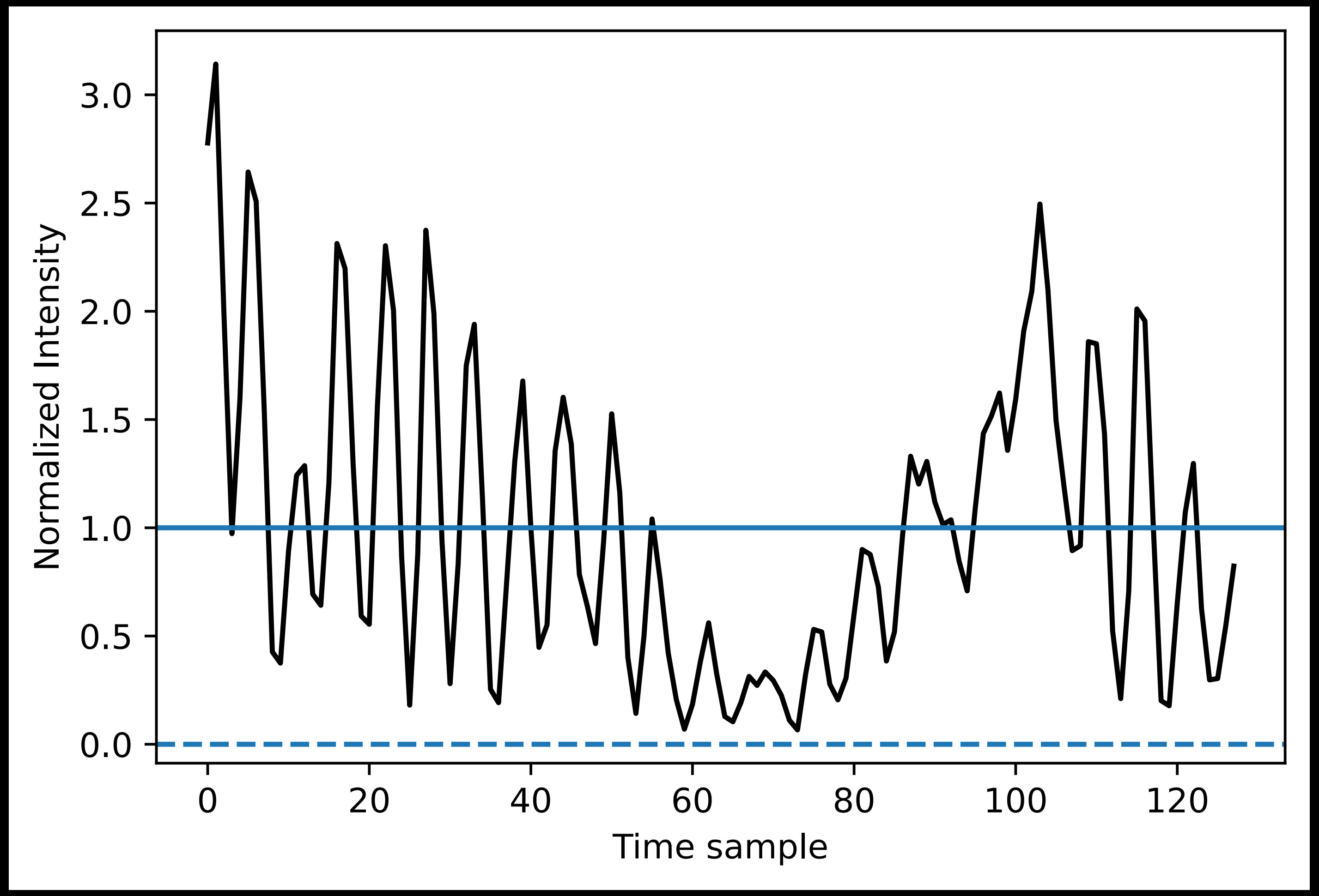


Given a signal... is it scintillated?



- Create bounding box around narrowband signal

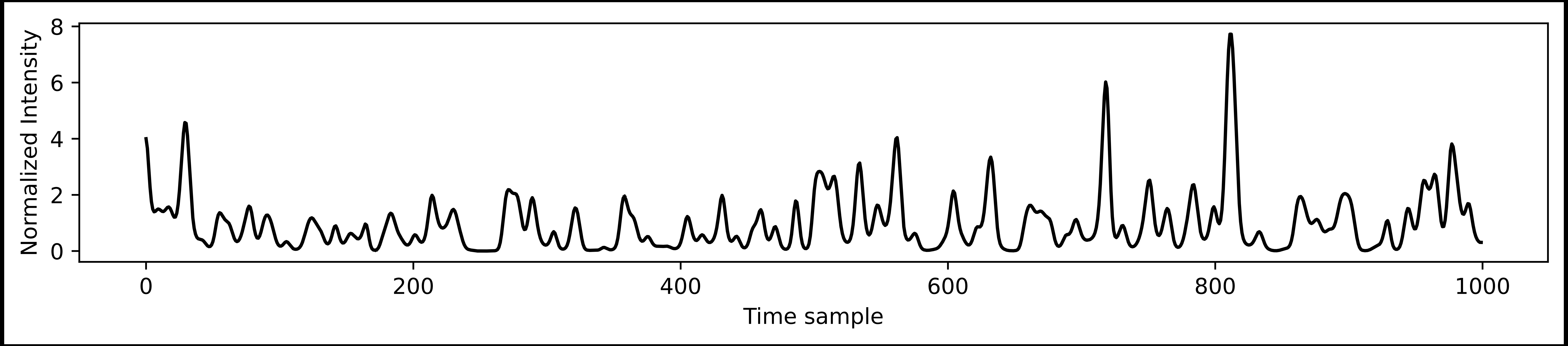
- Estimate noise-subtracted intensity **time series**, normalized to mean 1



- Compute diagnostic statistics that pertain to asymptotic behavior
  - E.g. standard deviation, Kolmogorov-Smirnoff statistic, fit to autocorrelation function

Quick way to produce synthetic data with asymptotic statistics

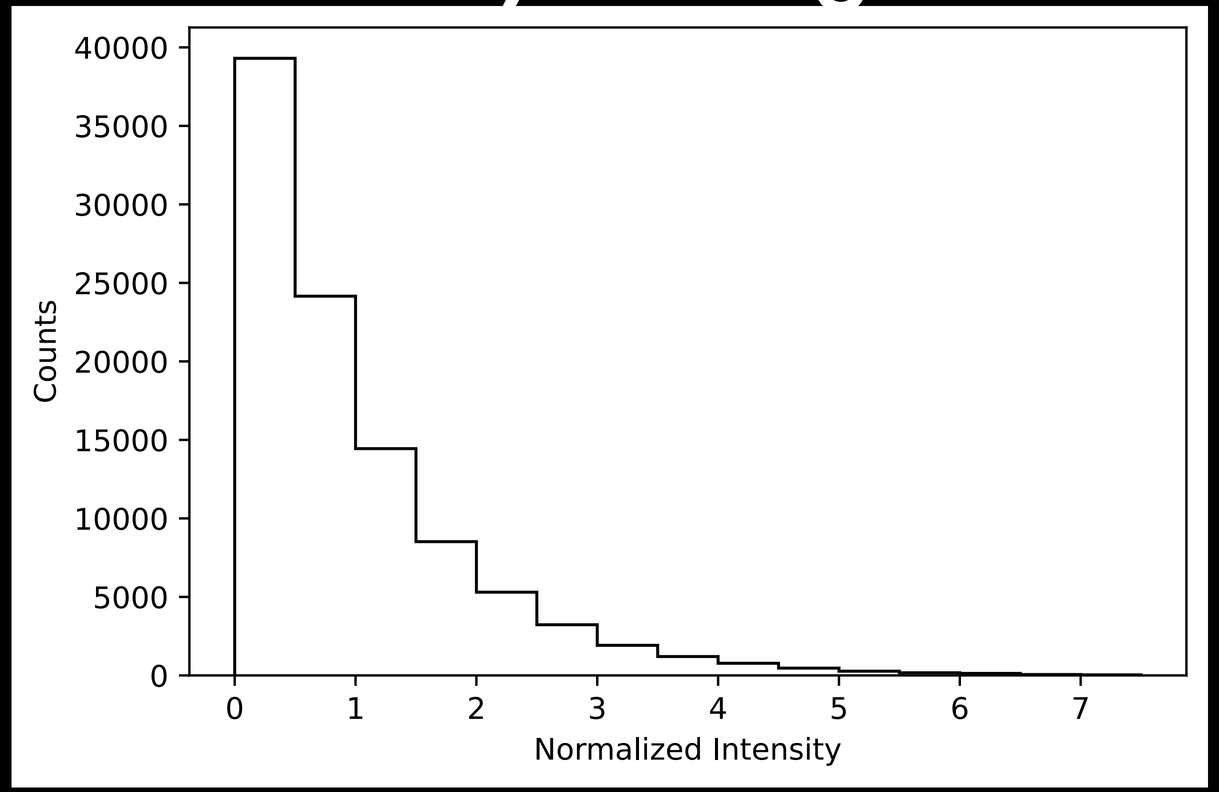
- (Cario & Nelson 1996) The ARTA random process matches:
  - Target intensity distribution
  - Target autocorrelation structure (with custom asymptotic precision)



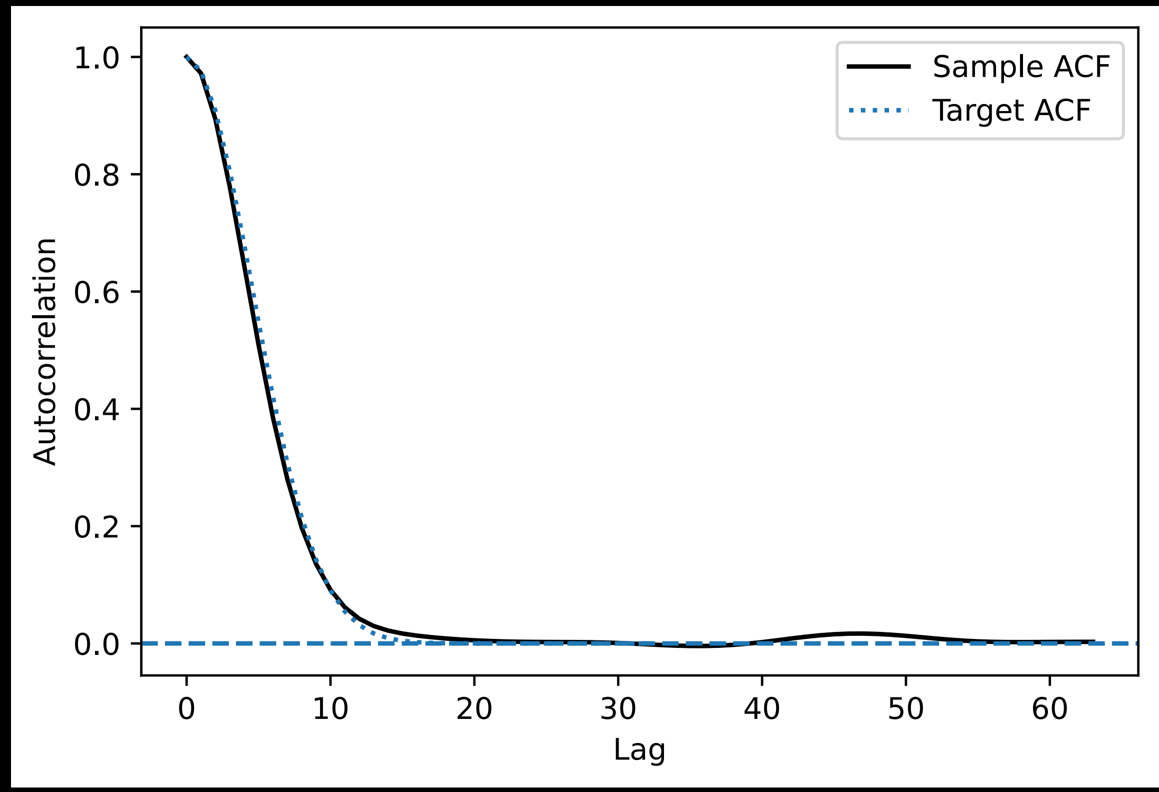
n = 1e5

$\Delta t_d = 30$ s

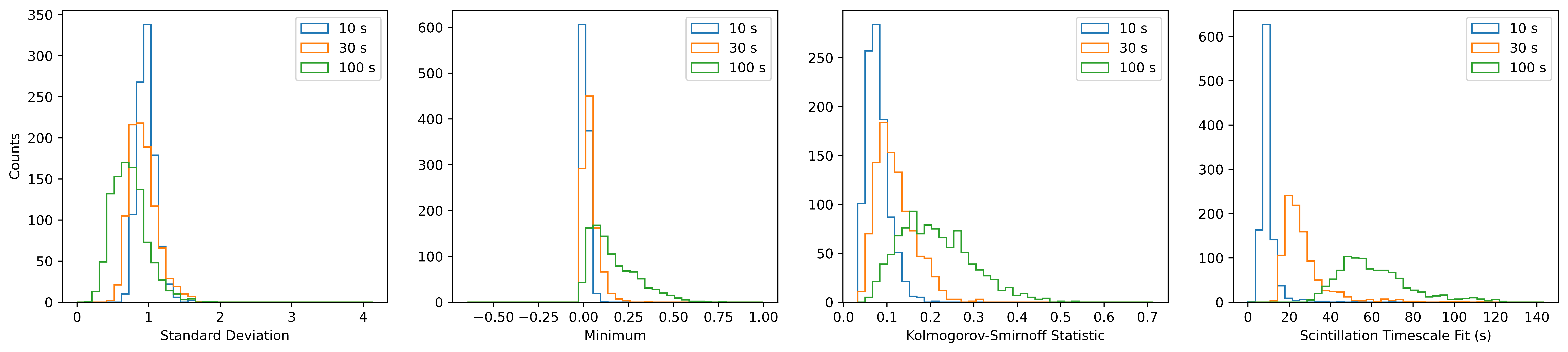
Intensity histogram



Autocorrelation



Statistics using low number of synthetic samples



Std. Dev.

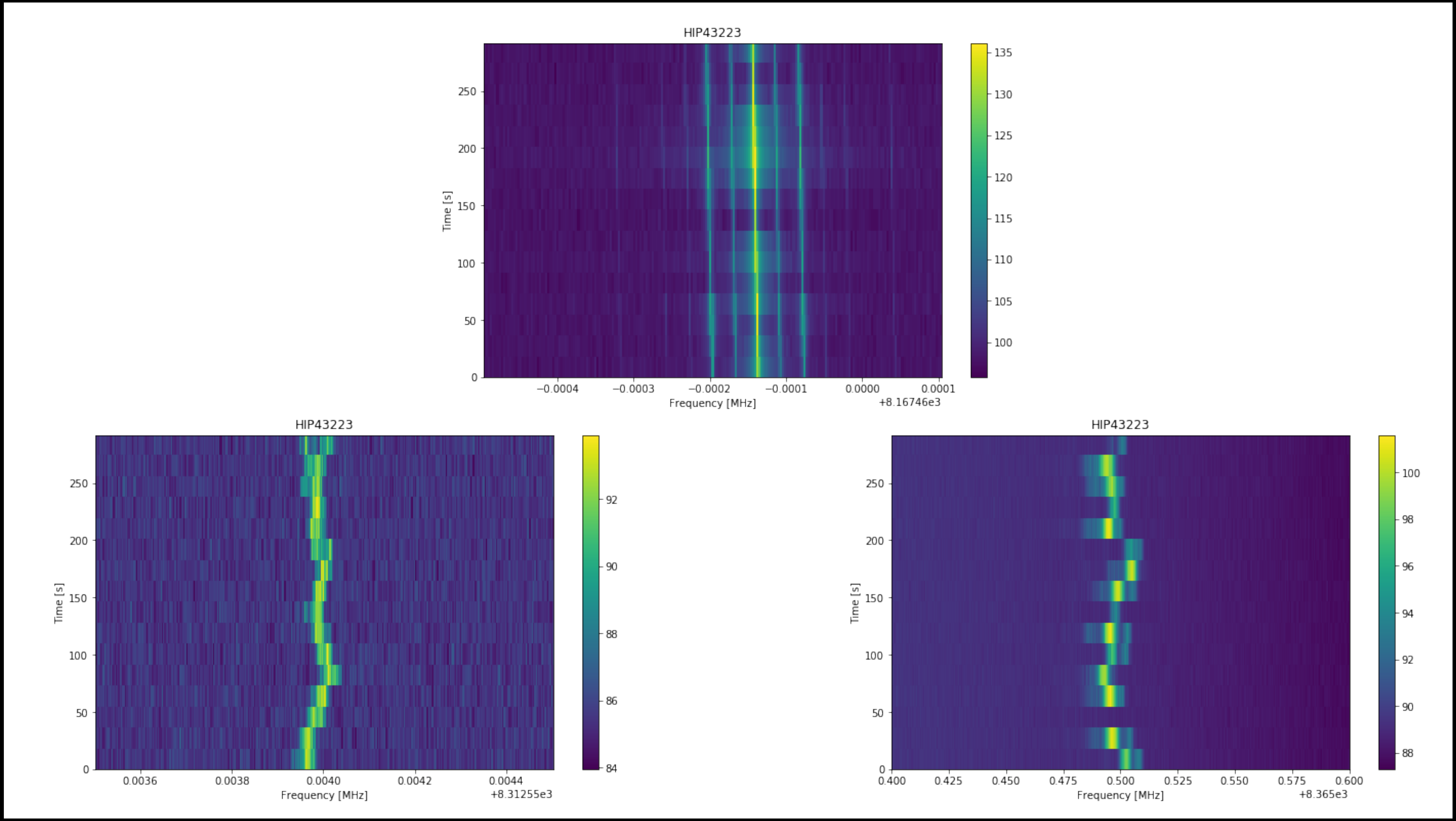
Minimum

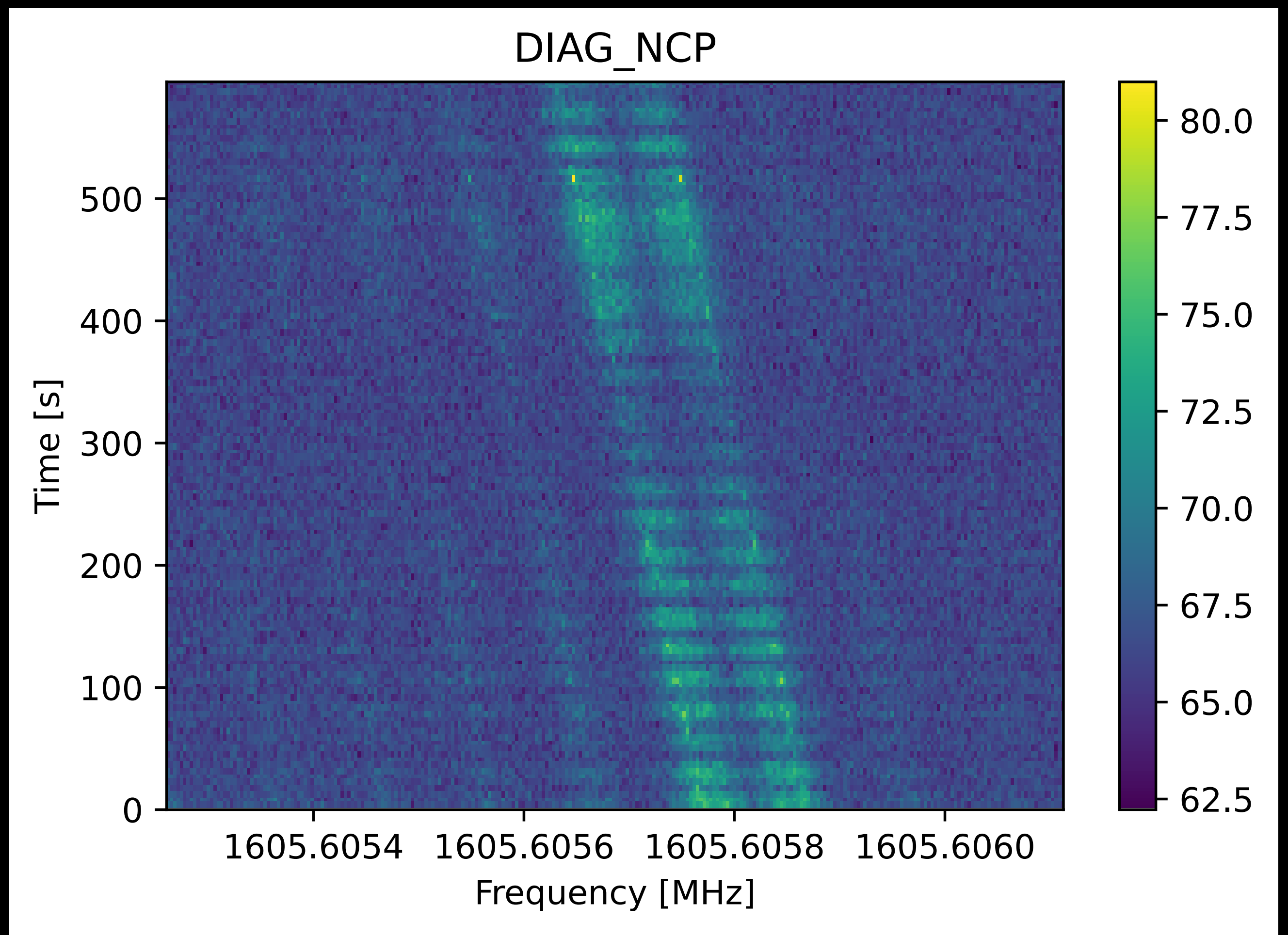
KS Statistic

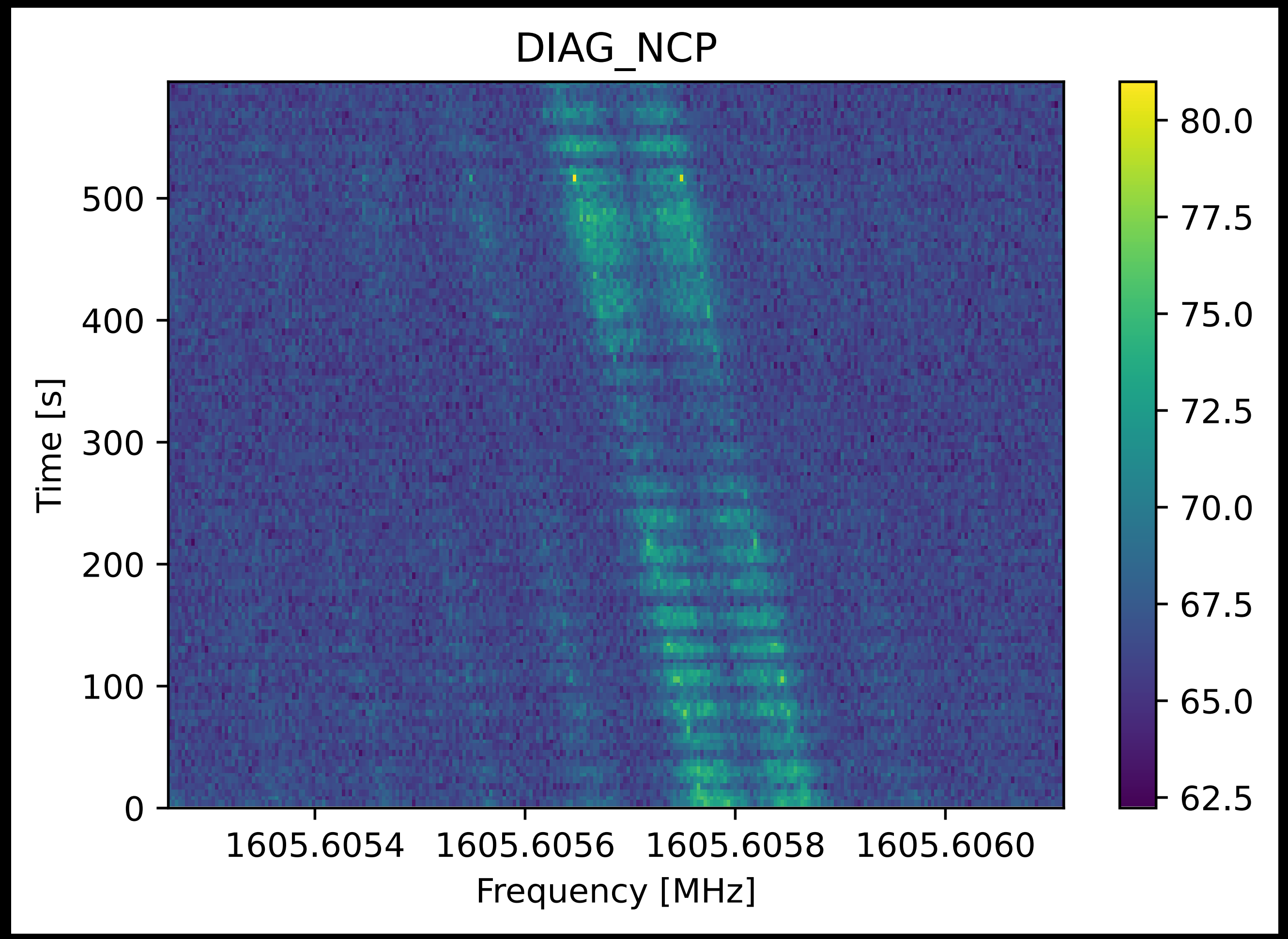
Timescale Fit

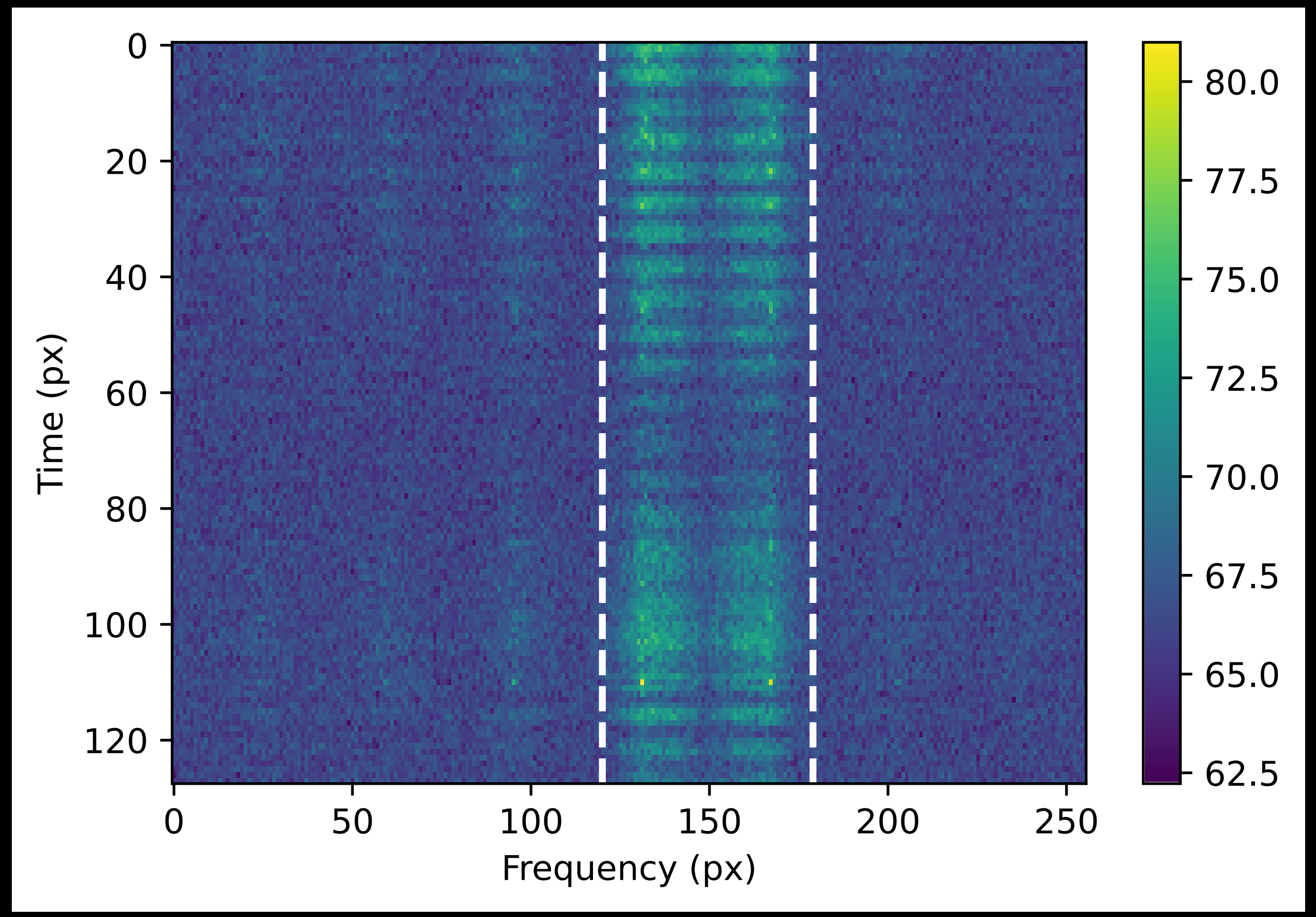
10 min "observation", 4.65 s

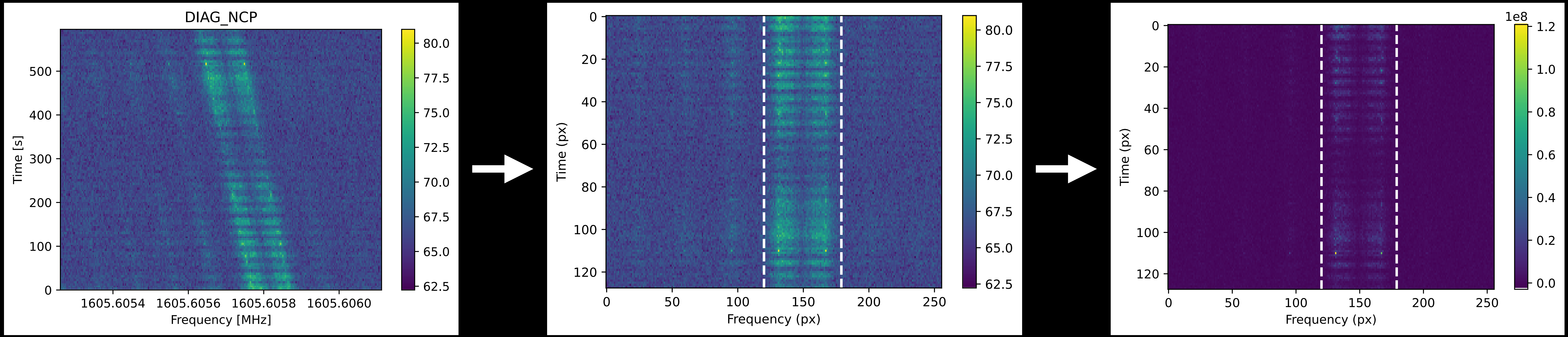
But what does the RFI environment look like?

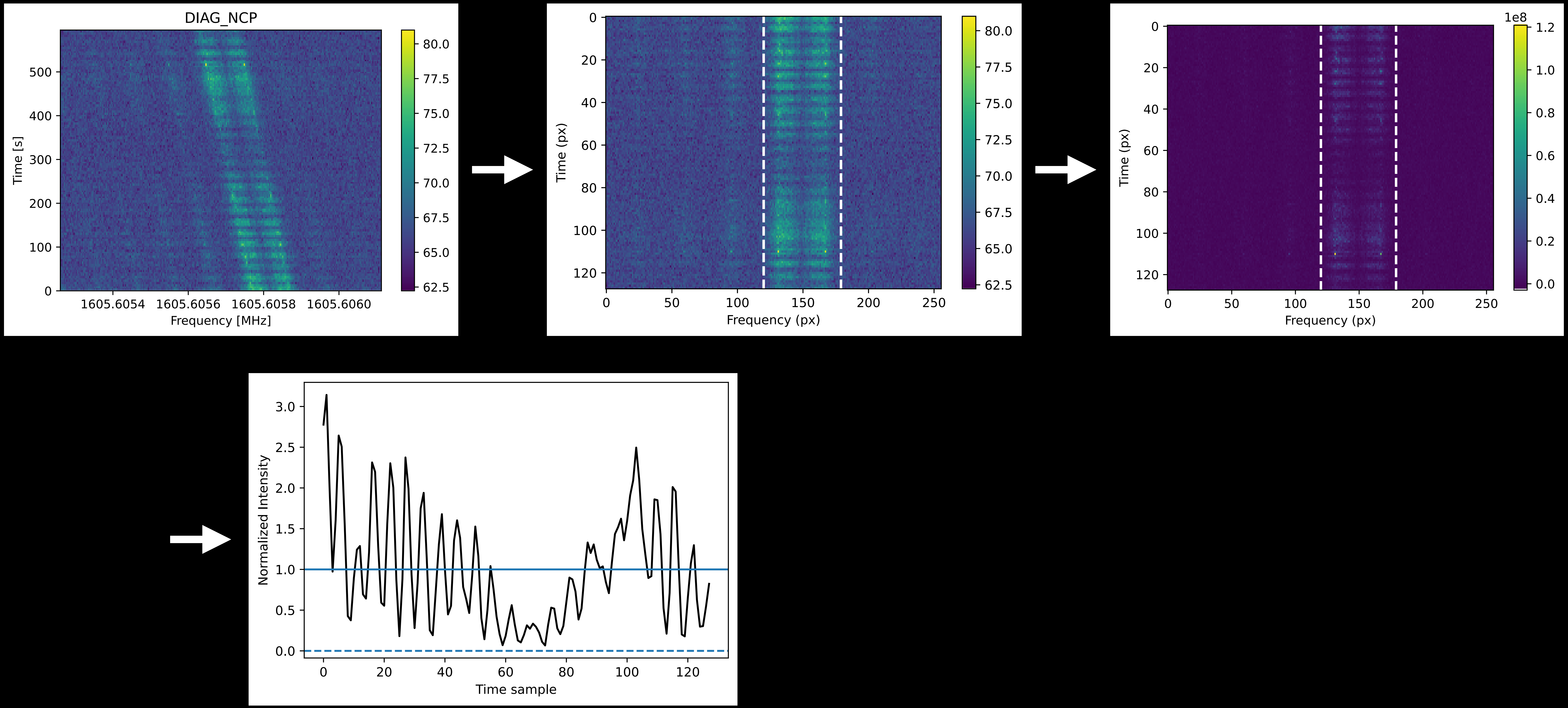


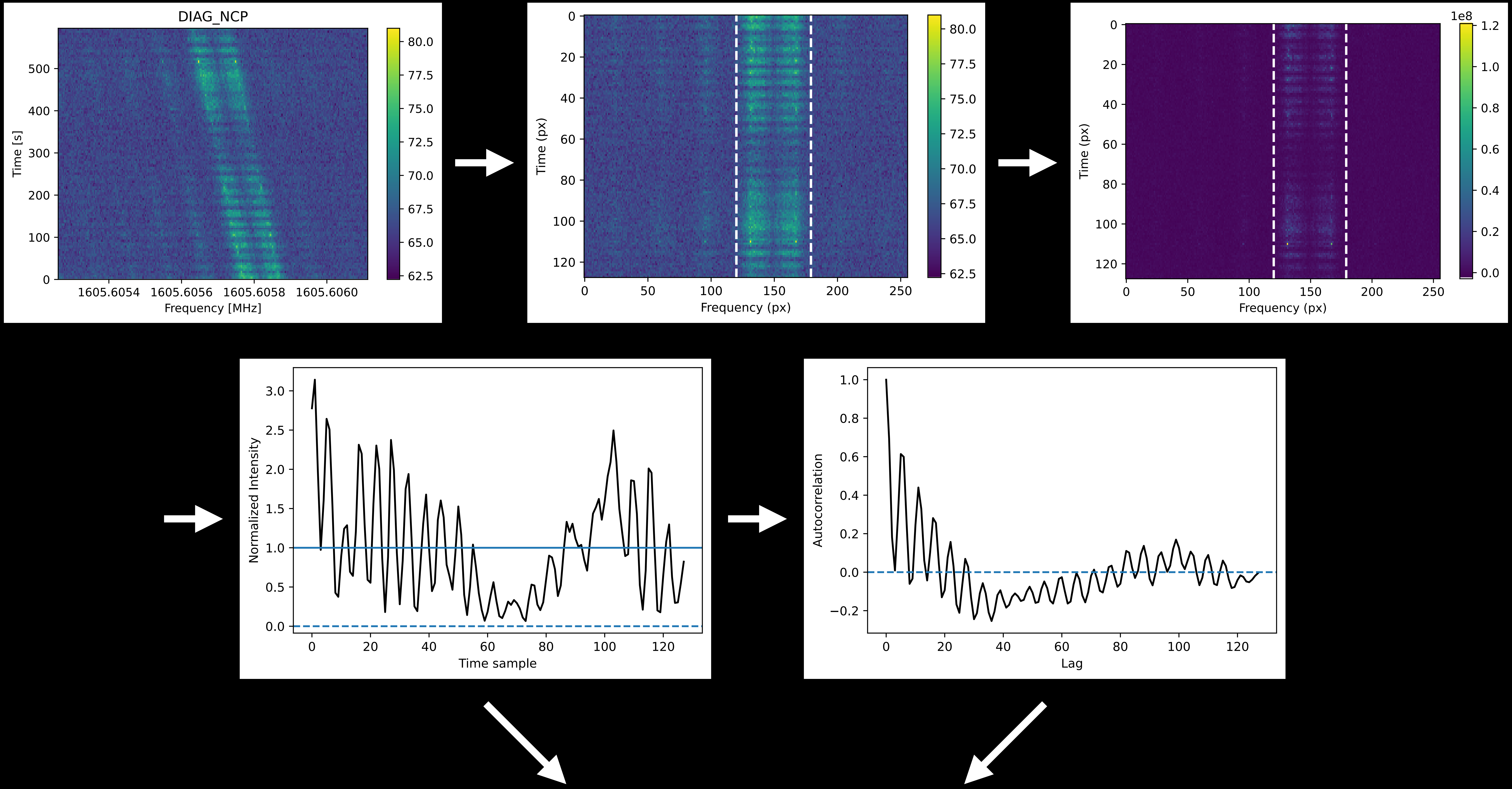

DIAG_NCP
Time [s]
500
400
300
200
100
0
1605.6054
1605.6056
1605.6058
1605.6060
Frequency [MHz]
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5


DIAG_NCP
Time [s]
500
400
300
200
100
0
1605.6054
1605.6056
1605.6058
1605.6060
Frequency [MHz]
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5


Time (px)
0
20
40
60
80
100
120
0
50
100
150
200
250
Frequency (px)
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5


DIAG_NCP
Time [s]
Frequency [MHz]
1605.6054
1605.6056
1605.6058
1605.6060
Time (px)
Frequency (px)
1e8

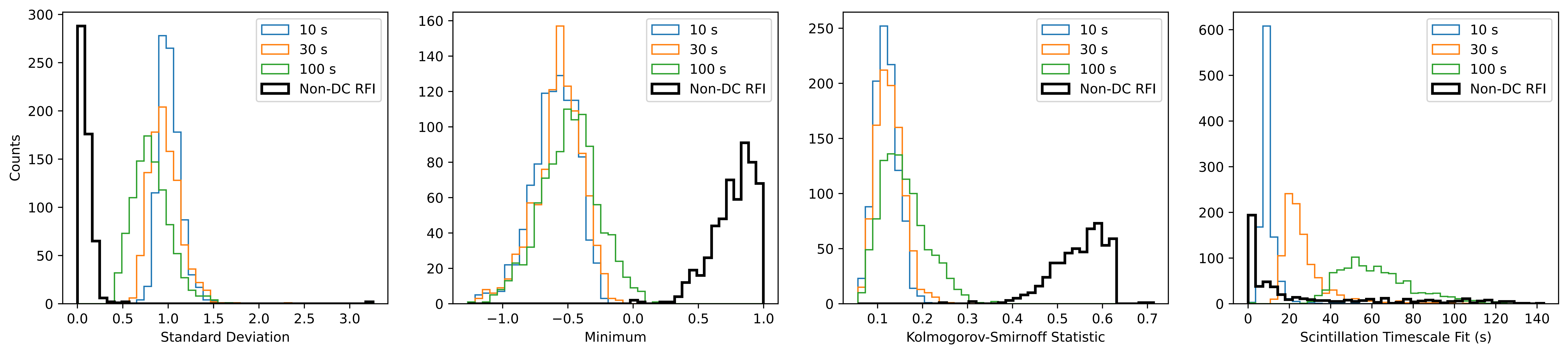

DIAG_NCP
Time [s]
0
100
200
300
400
500
1605.6054
1605.6056
1605.6058
1605.6060
Frequency [MHz]
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
Time (px)
0
20
40
60
80
100
120
0
50
100
150
200
250
Frequency (px)
1e8
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Normalized Intensity
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time sample



Diagnostic statistics

C band

S/N = 25



Std. Dev. | Minimum | KS Statistic | Timescale Fit

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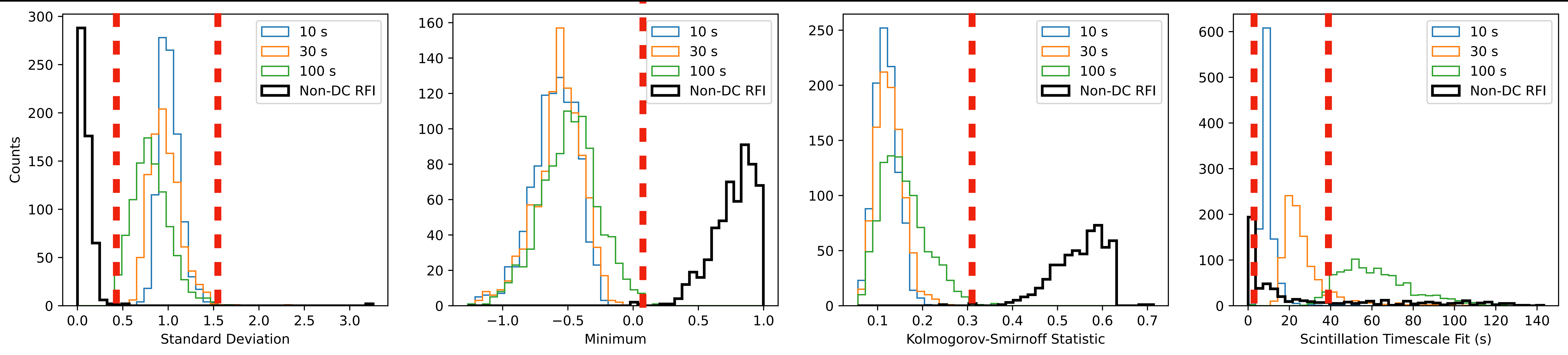
BREAKTHROUGH LISTEN

C band

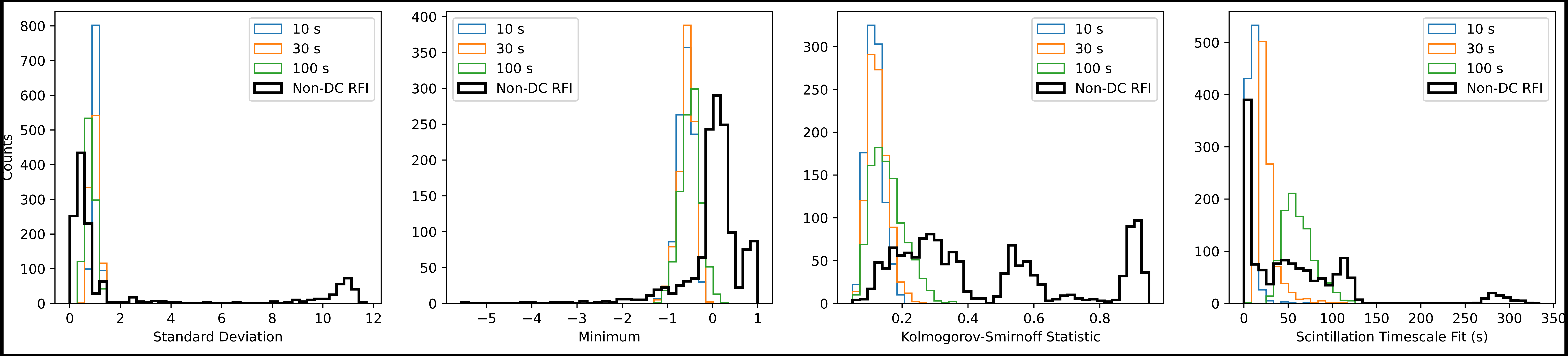
S/N = 25



Std. Dev.   Minimum   KS Statistic   Timescale Fit

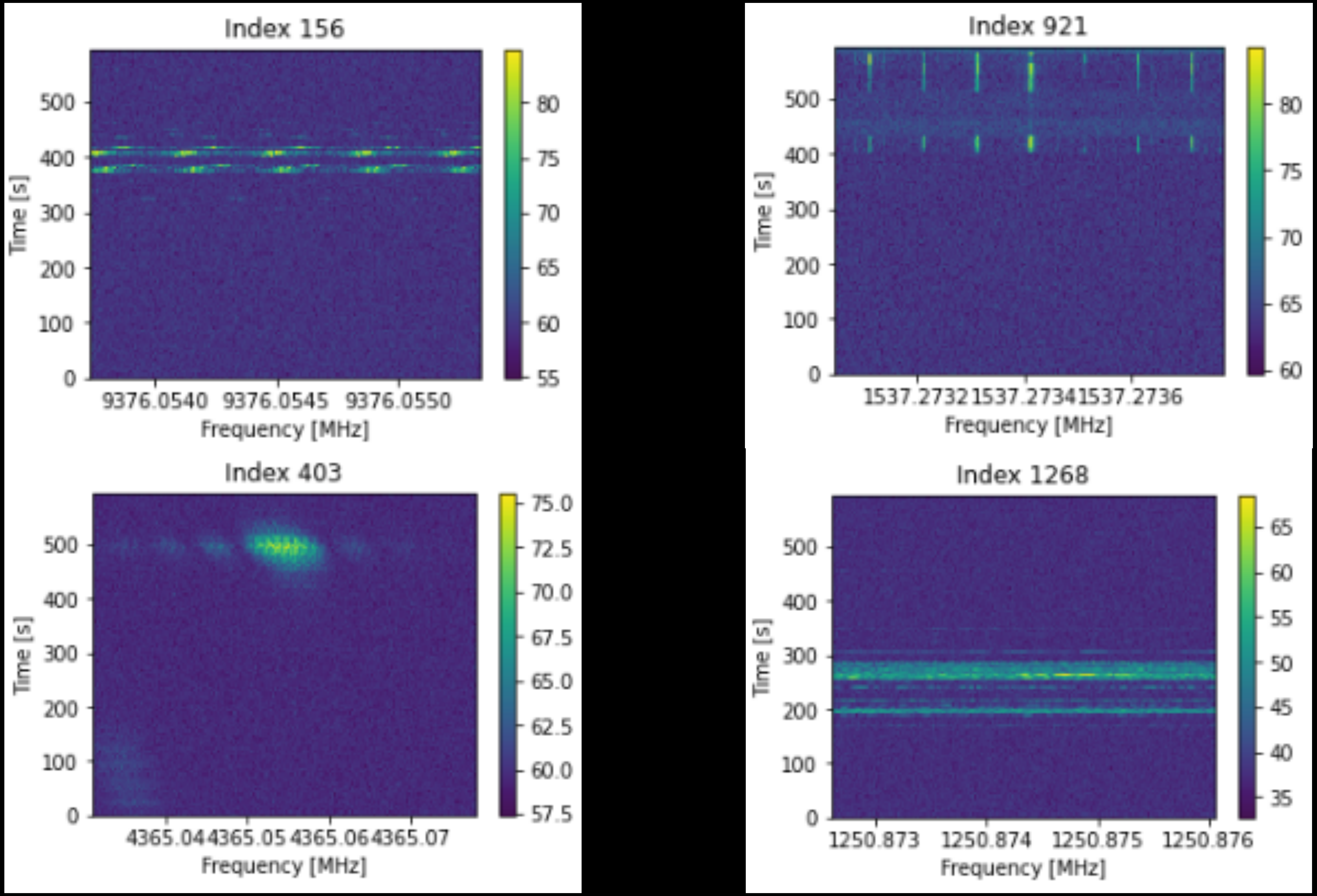
L band

S/N = 25

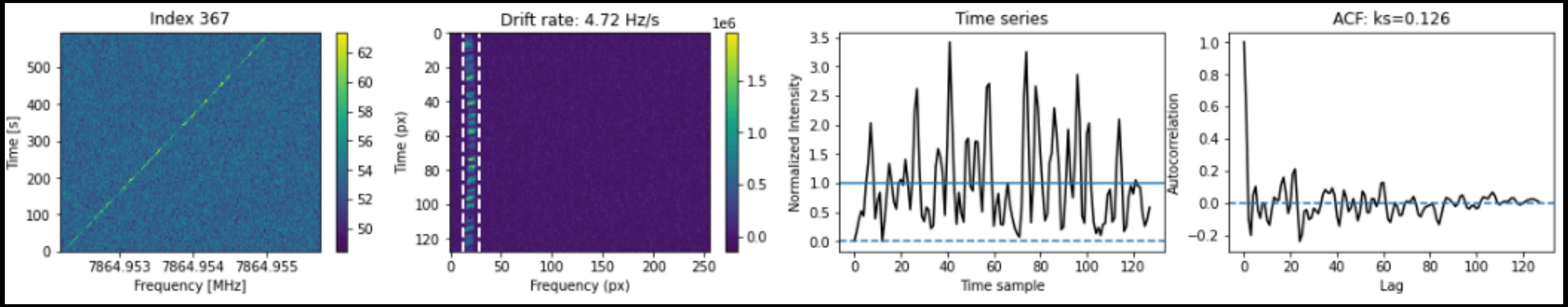


Std. Dev.   Minimum   KS Statistic   Timescale Fit

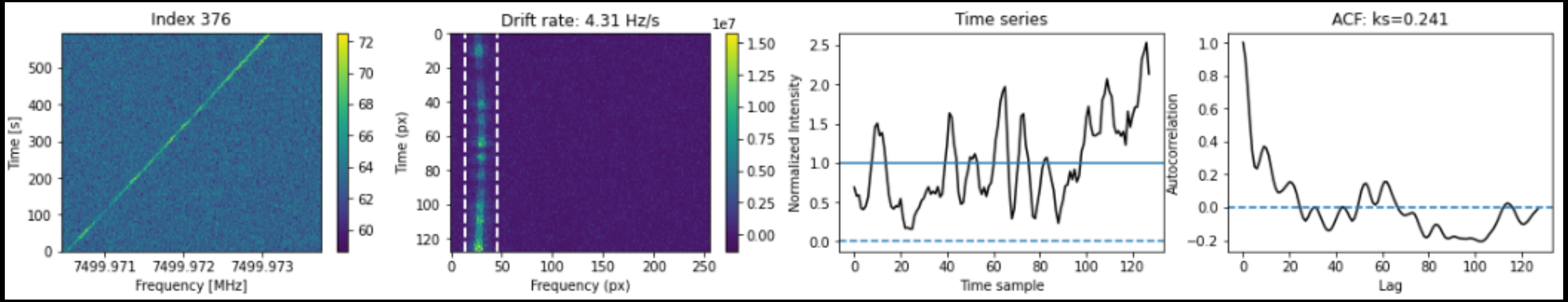
High standard deviation (RMS) signals are pulsed - or broadband



What signals pass the threshold?



Timescale fit ~ 2 s

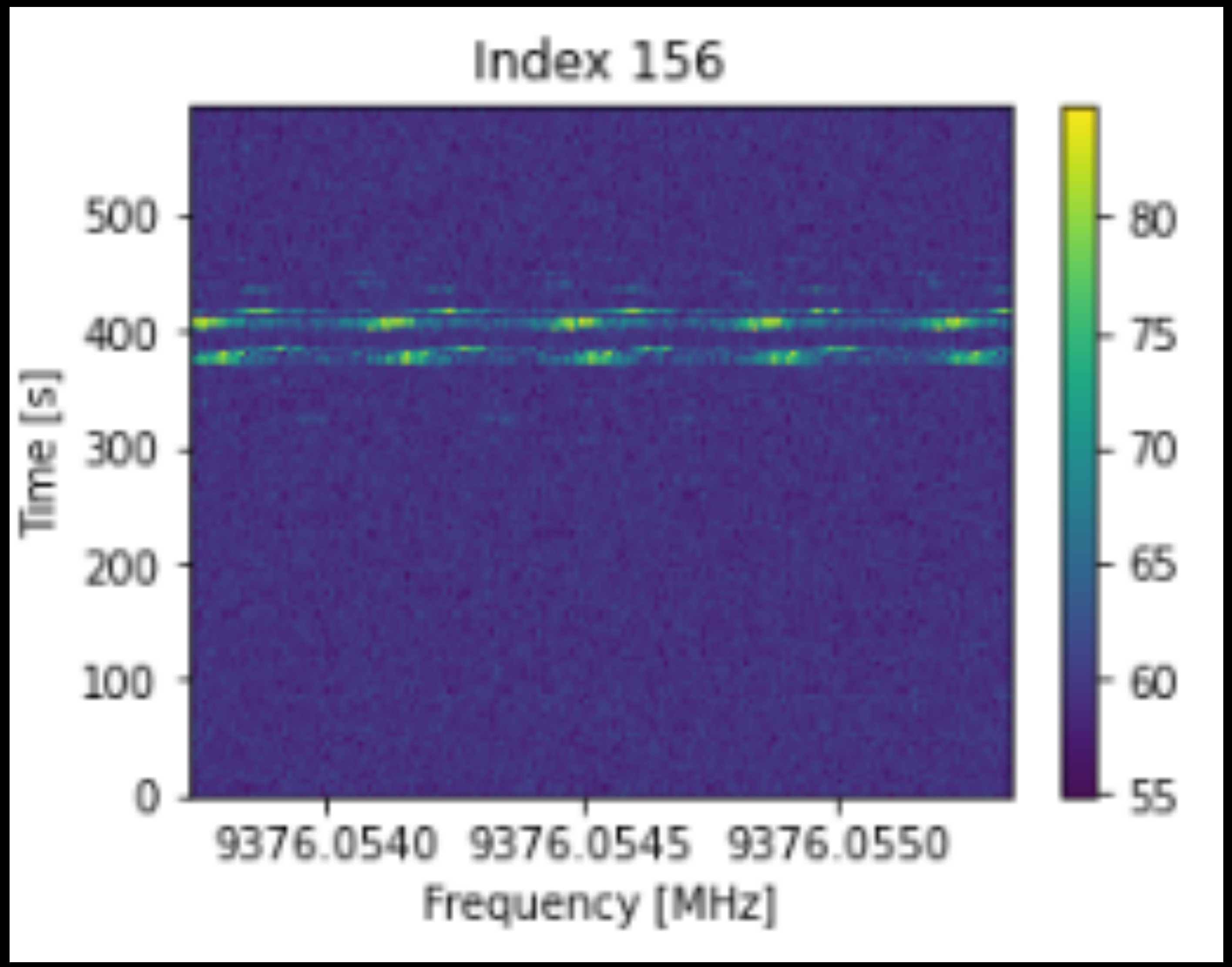


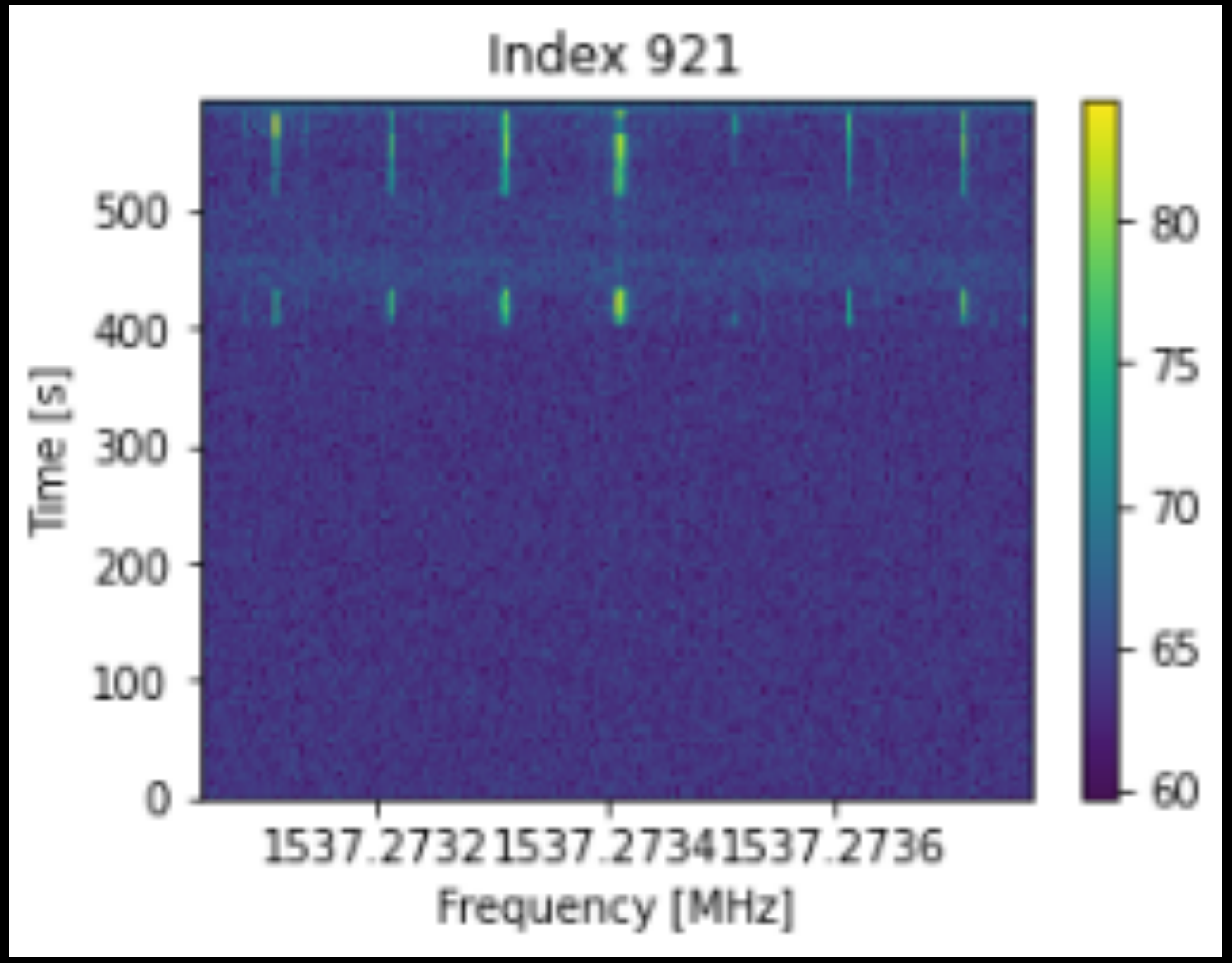
Timescale fit ~ 60 s

- At C-band, S/N > 25, 3 out of 1102

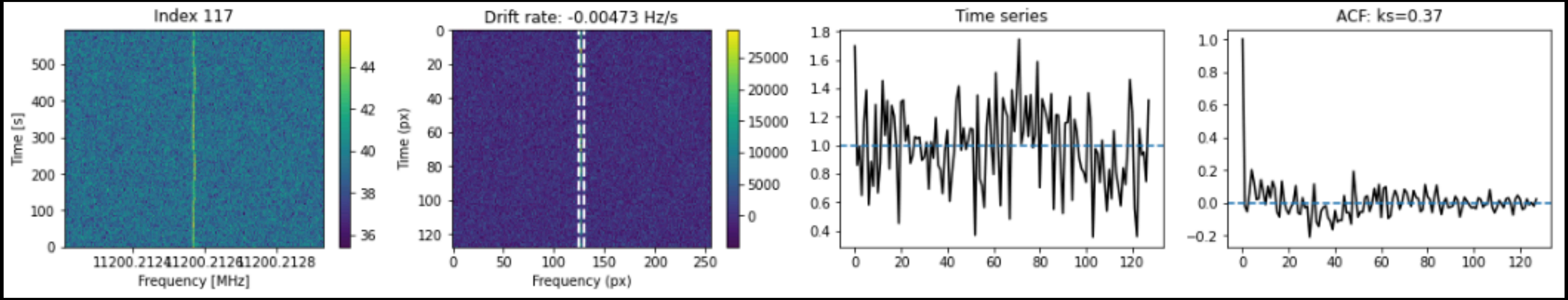
Limitations from RFI analysis?

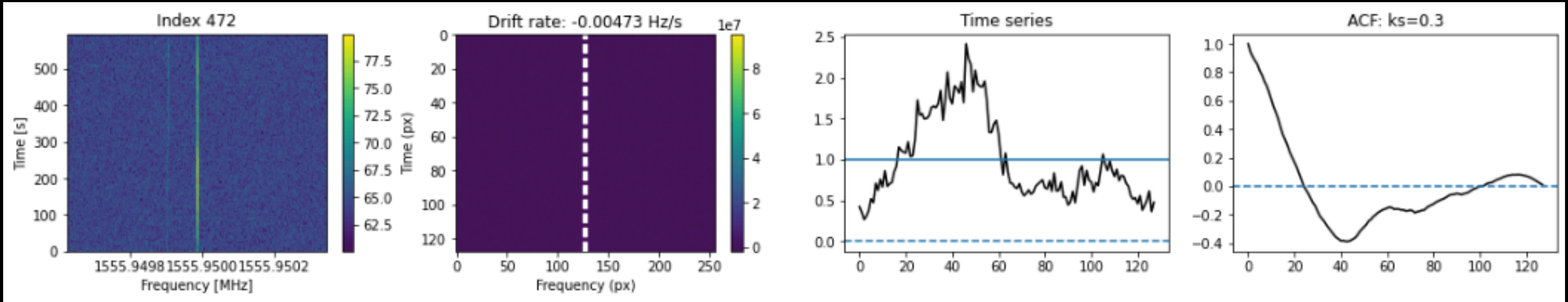
- L and S bands in particular are very noisy
- Non-narrowband signals detected just because they are above the SNR threshold
- Difficult to apply a one-size-fits-all bounding box method
- Perhaps ML can help!



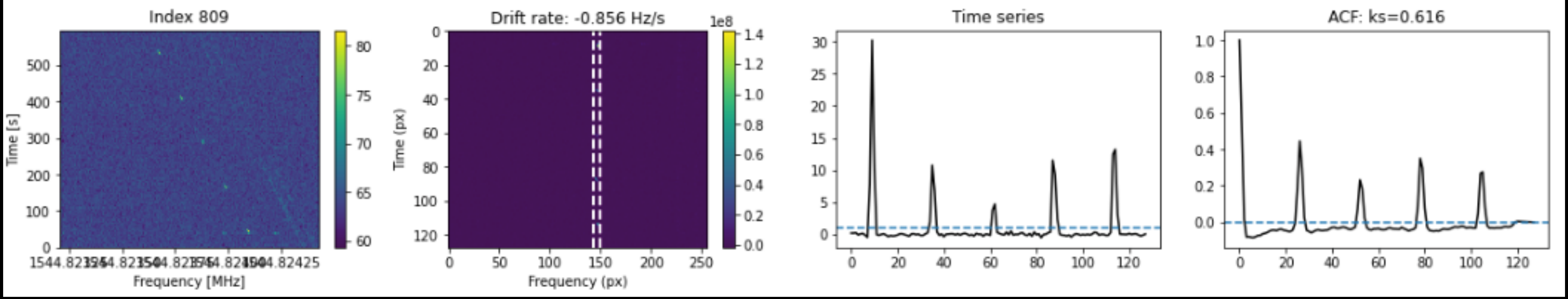


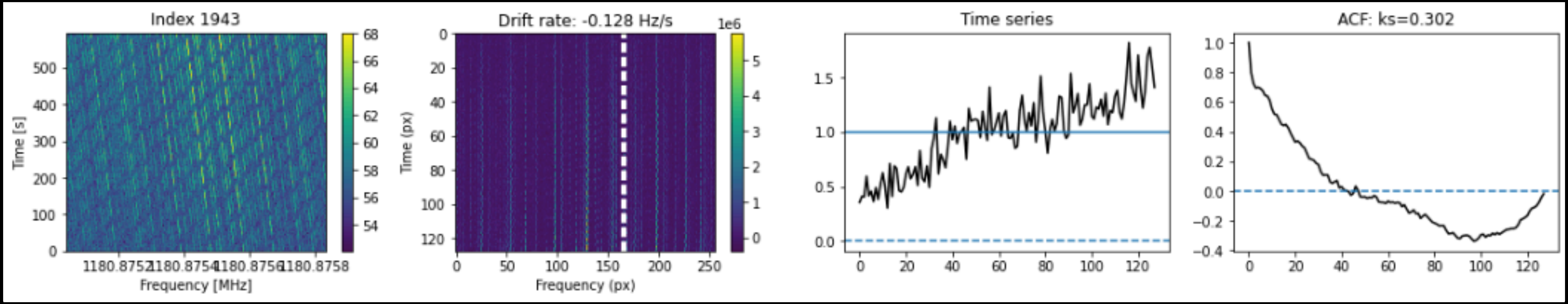
Some examples





Some more examples





Examples of diagnostic statistics

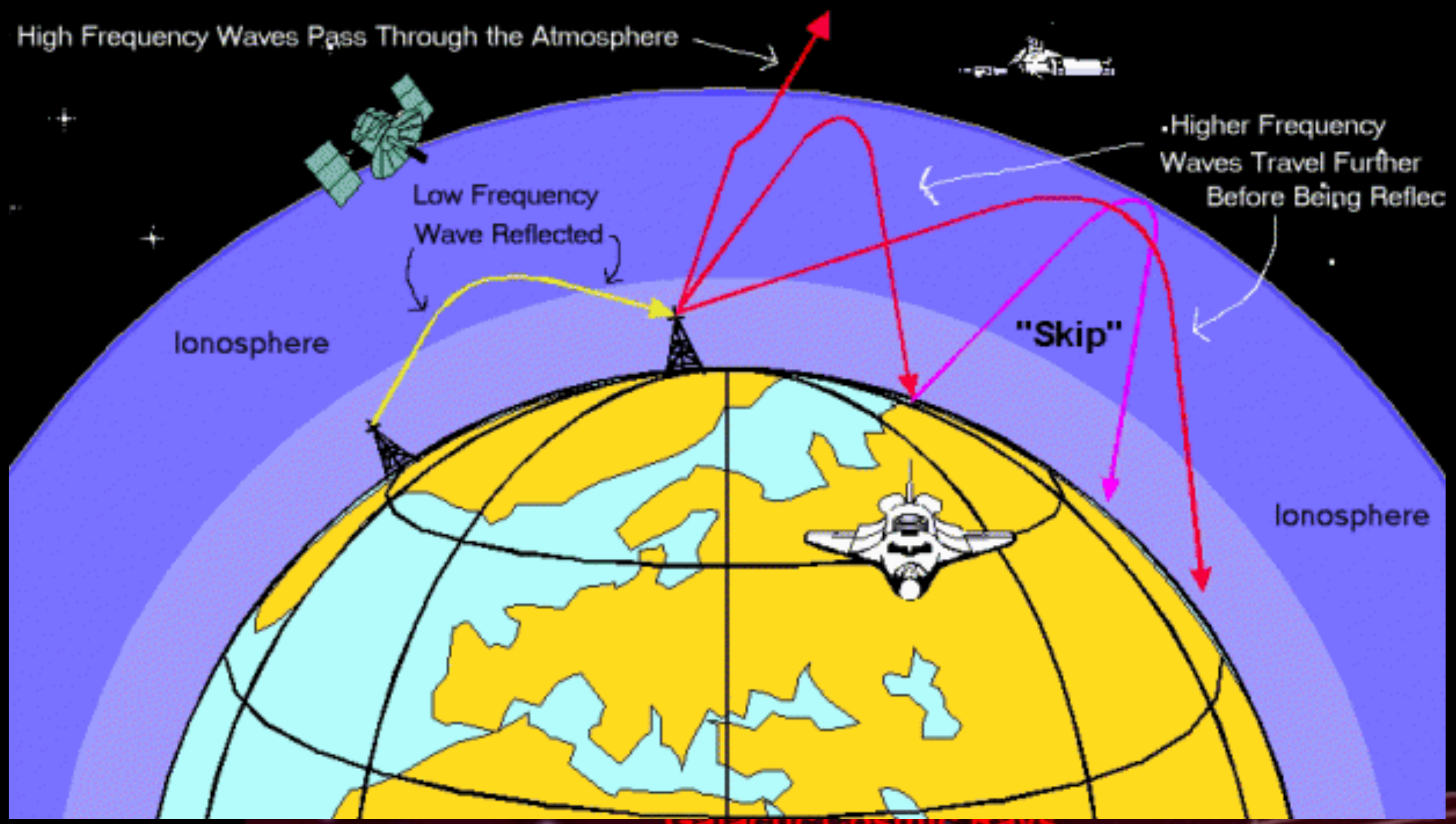
Statistic	Asymptotic Value (with no noise)	Target Distribution
Standard Deviation (RMS)	1	Intensity, exponential
Minimum	0	Intensity, exponential
Kolmogorov-Smirnoff statistic	0	Intensity, exponential
Autocorrelation lag	Variable	Autocorrelation, Gaussian
Least squares fit to autocorrelation	Variable	Autocorrelation, Gaussian

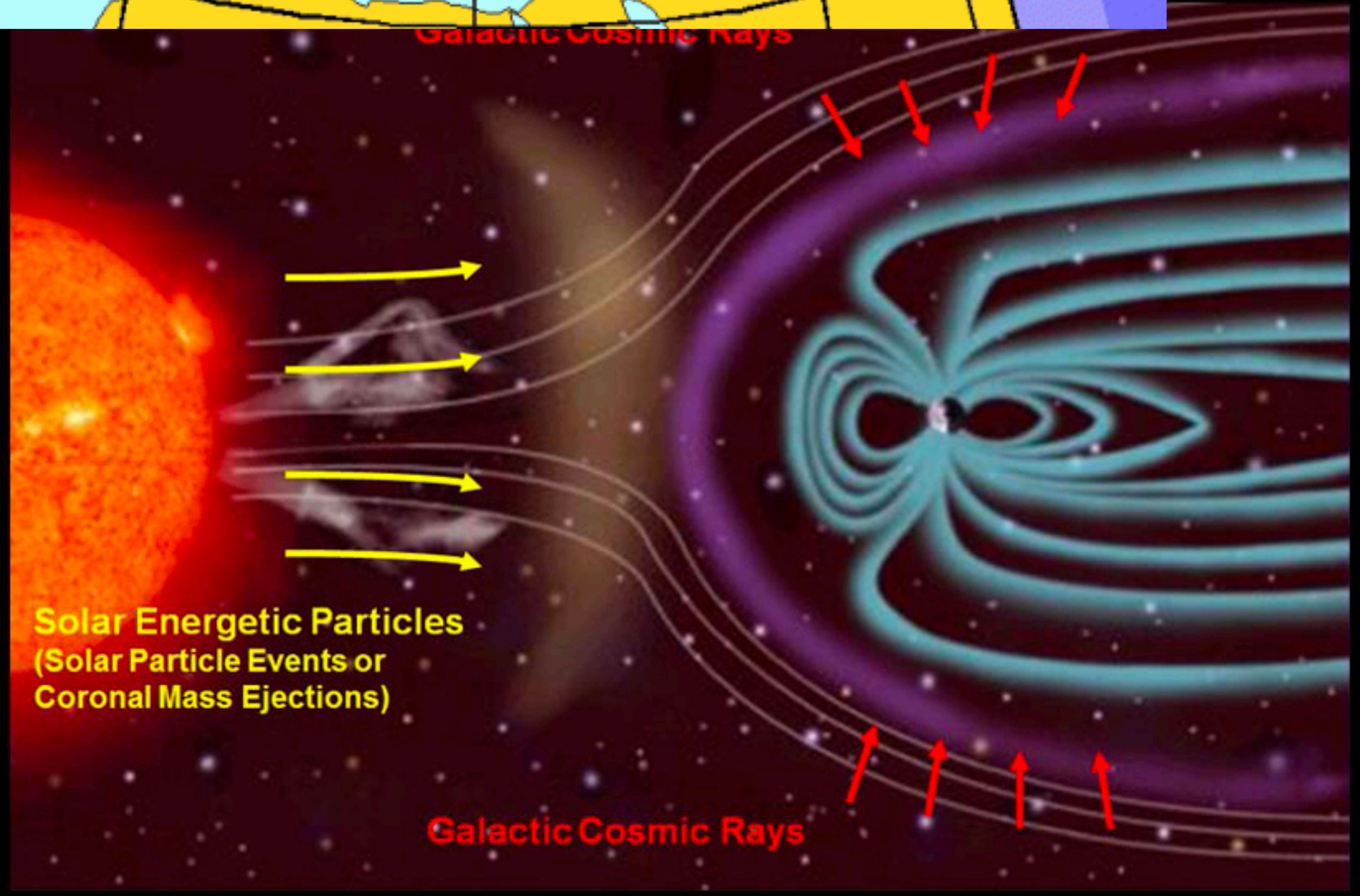
There are a number of constraints...

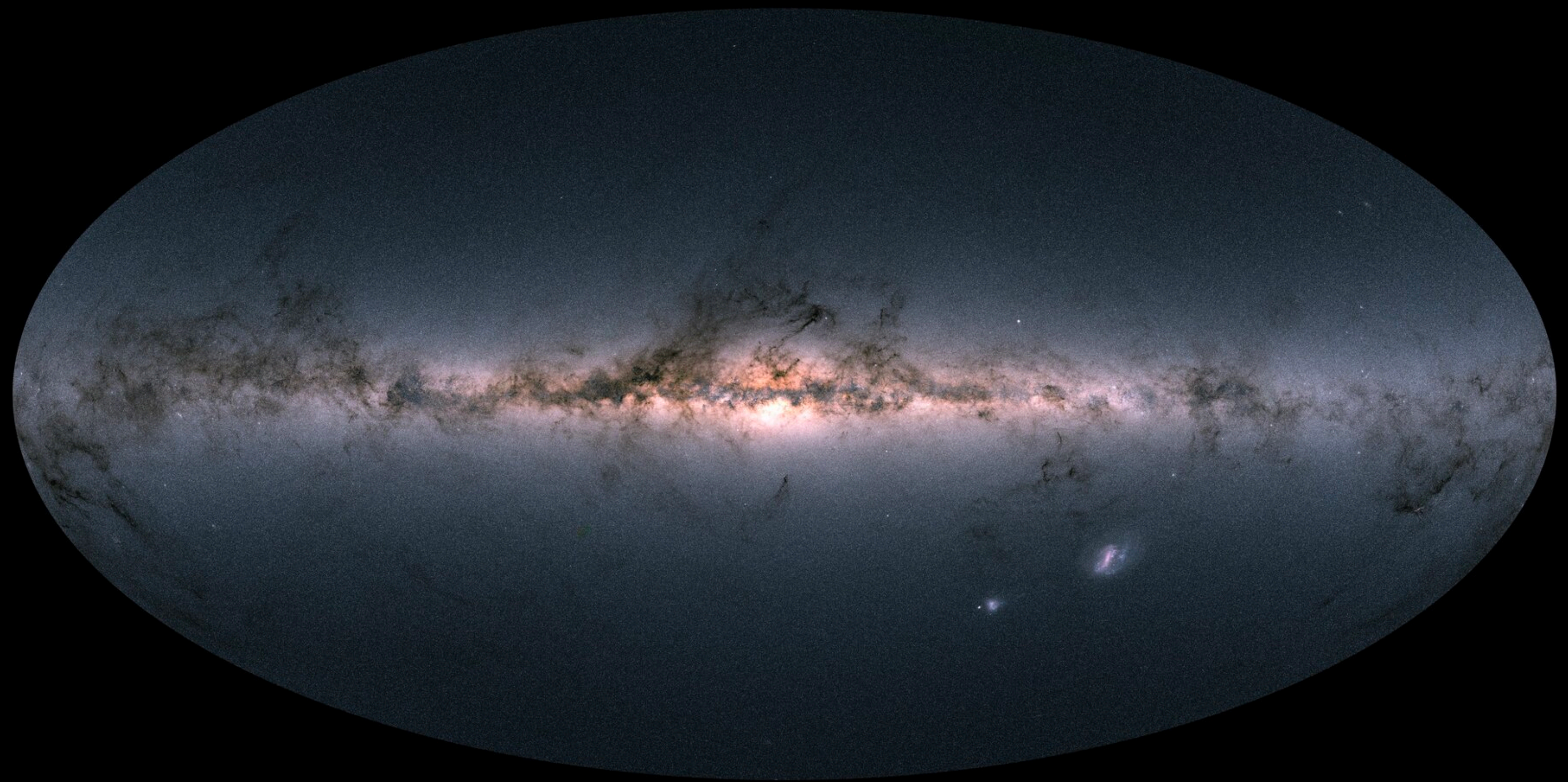
- Time resolution - Sufficiently resolve scintles
- Integration time - Collect enough scintles, gain stability
- Signal brightness - Compute accurate statistics embedded in noise
- RFI environment - Bad normalization, false narrowband detections, confounding modulation

Regions of ionized plasma

- Ionosphere
- Interplanetary Medium (IPM)
- Interstellar Medium (ISM)



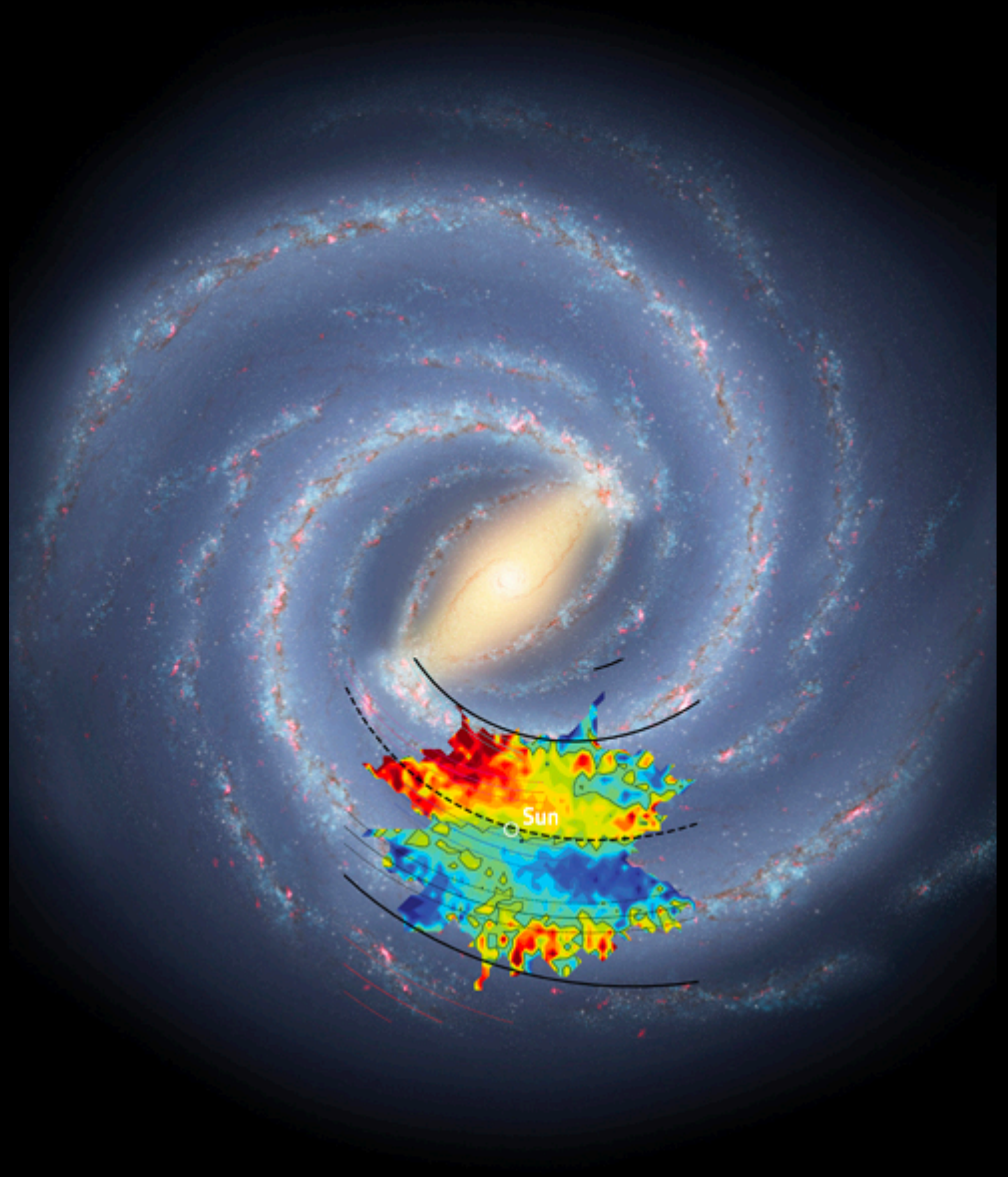




ROUGH

Next steps: a Galactic Center / Galactic Plane survey

- Target most promising sections of parameter space
- Survey of Galactic plane with interesting targets
- Gaia DR3?



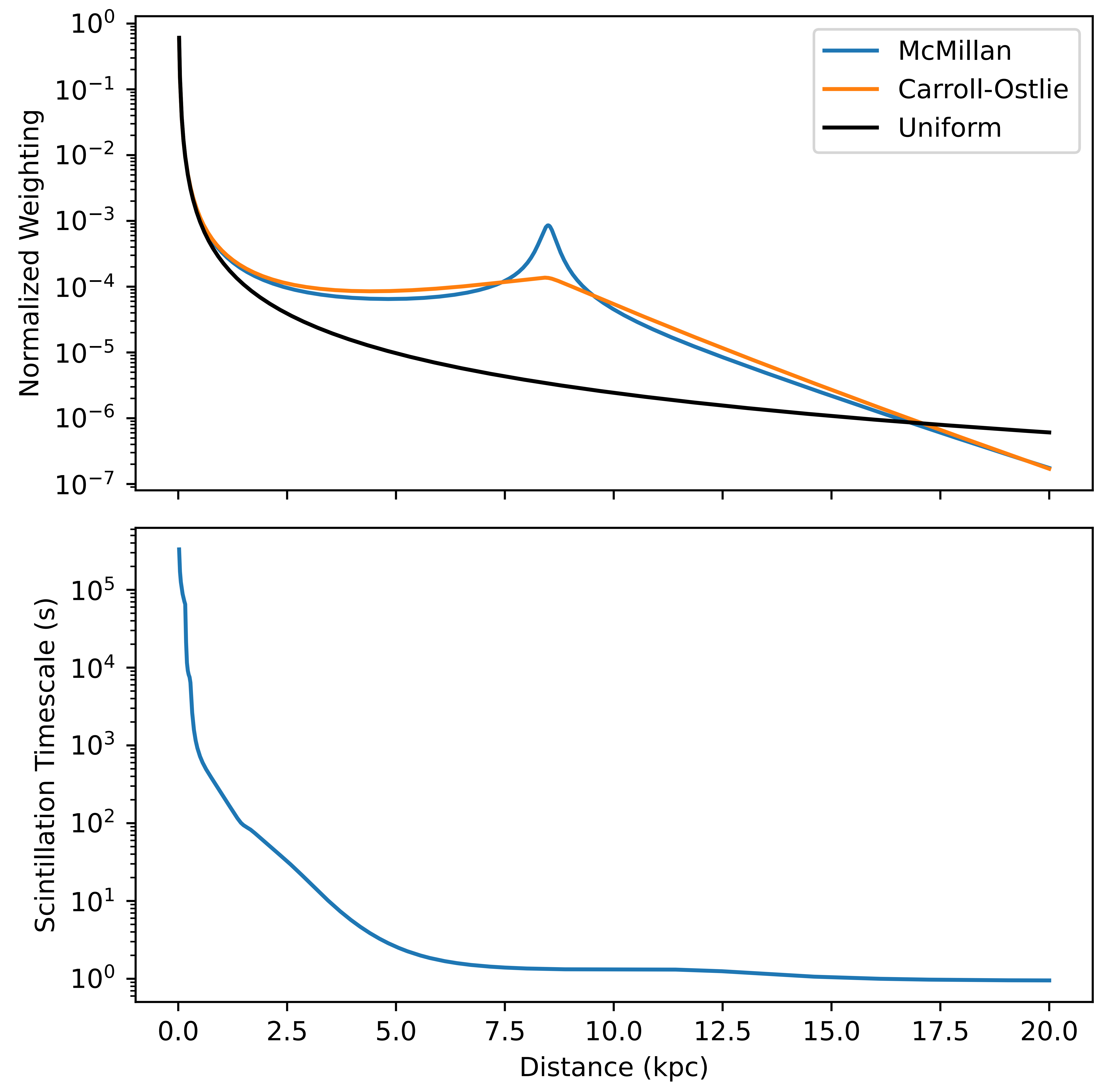
Gaia

Density-based sampling

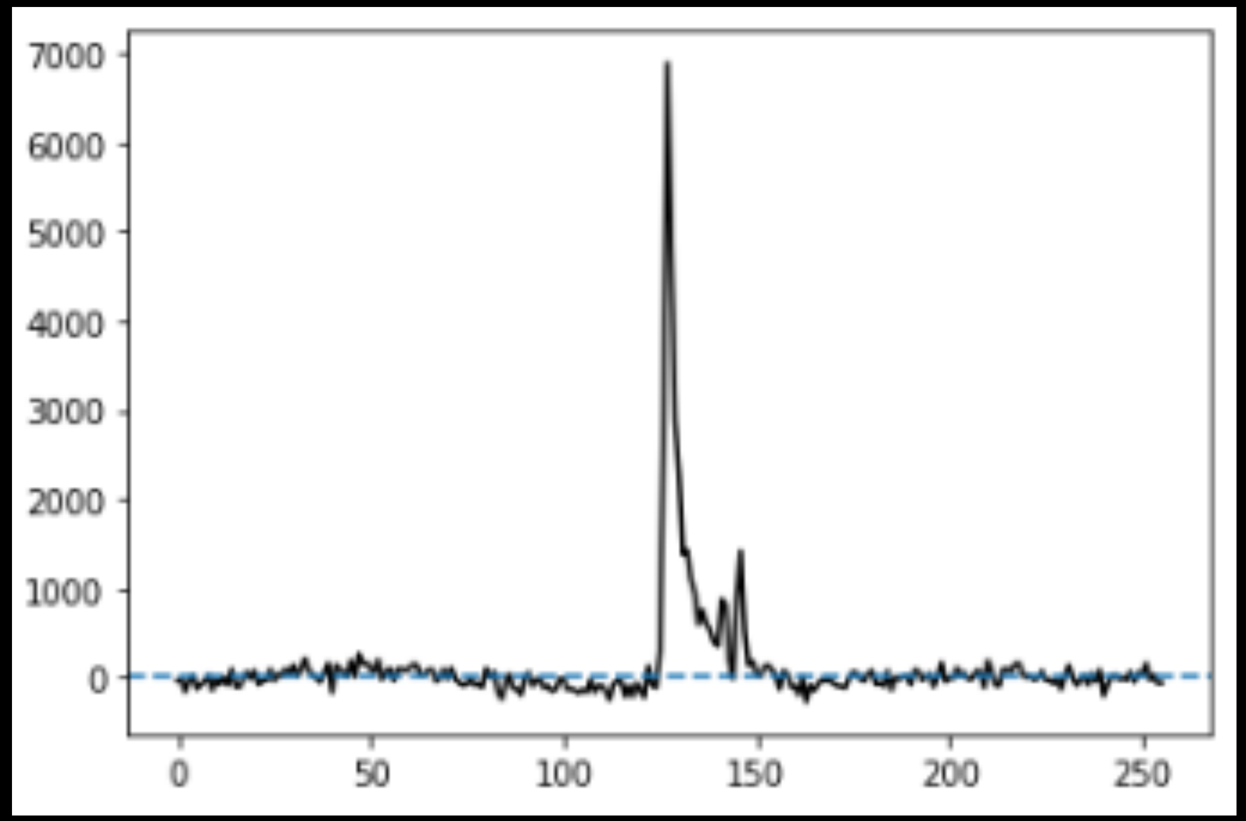
Modulating by the inverse square-law for detectability:

Depends on the assumptions made about transmission power and resources.

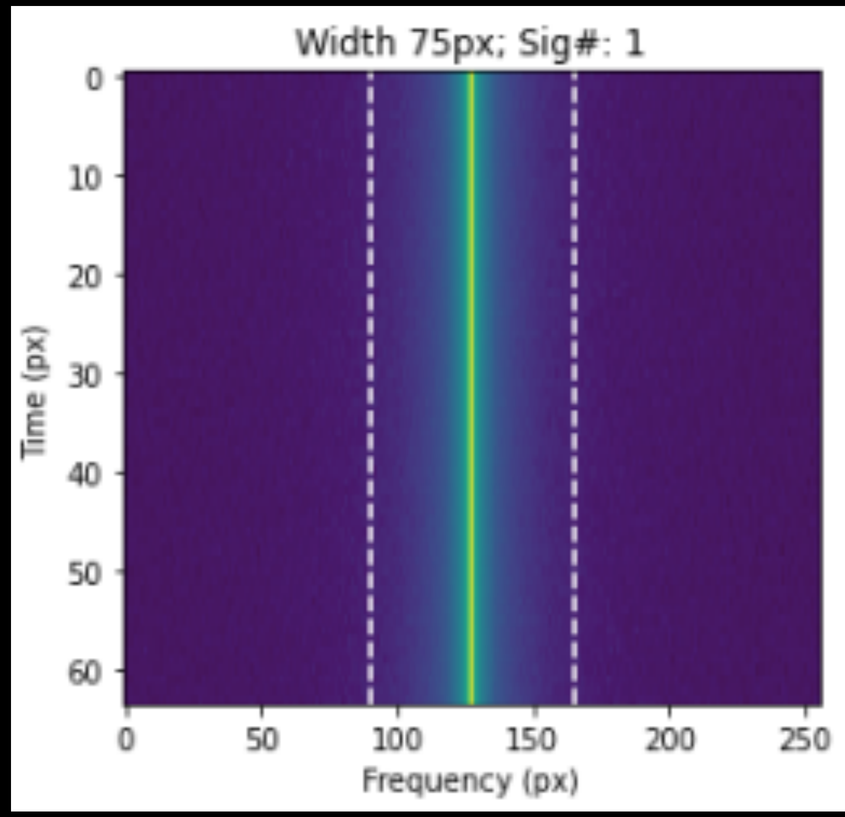
(l, b) = (1, 0)



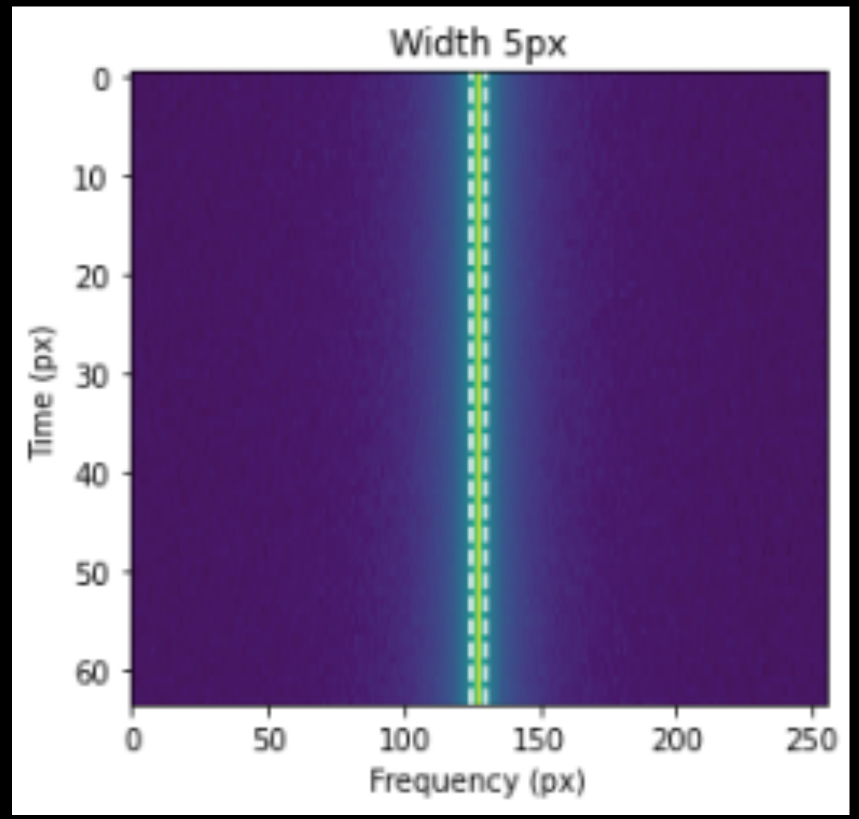
Selecting bounding boxes



- After experimentation with various methods, the final pipeline uses a combination of baseline fitting and peak detection to calculate the right size of frame to use
- The final bounds are created using a thresholding method, similar to PSRCHIVE
- Take the final bounded signal and integrate in the frequency direction to derive our raw time series – then we normalize to mean of 1 before calculating our scattering statistics



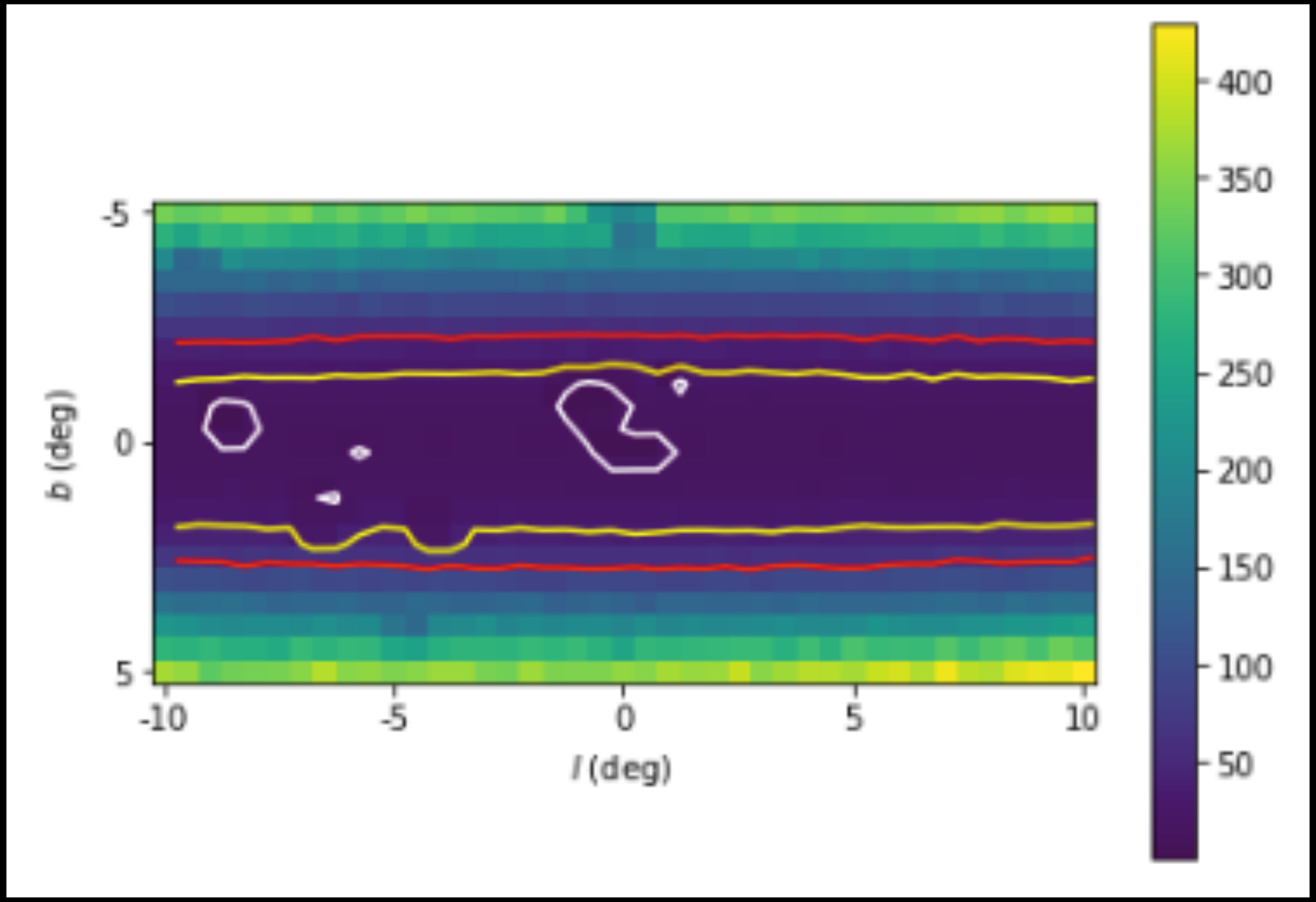
Polynomial fit



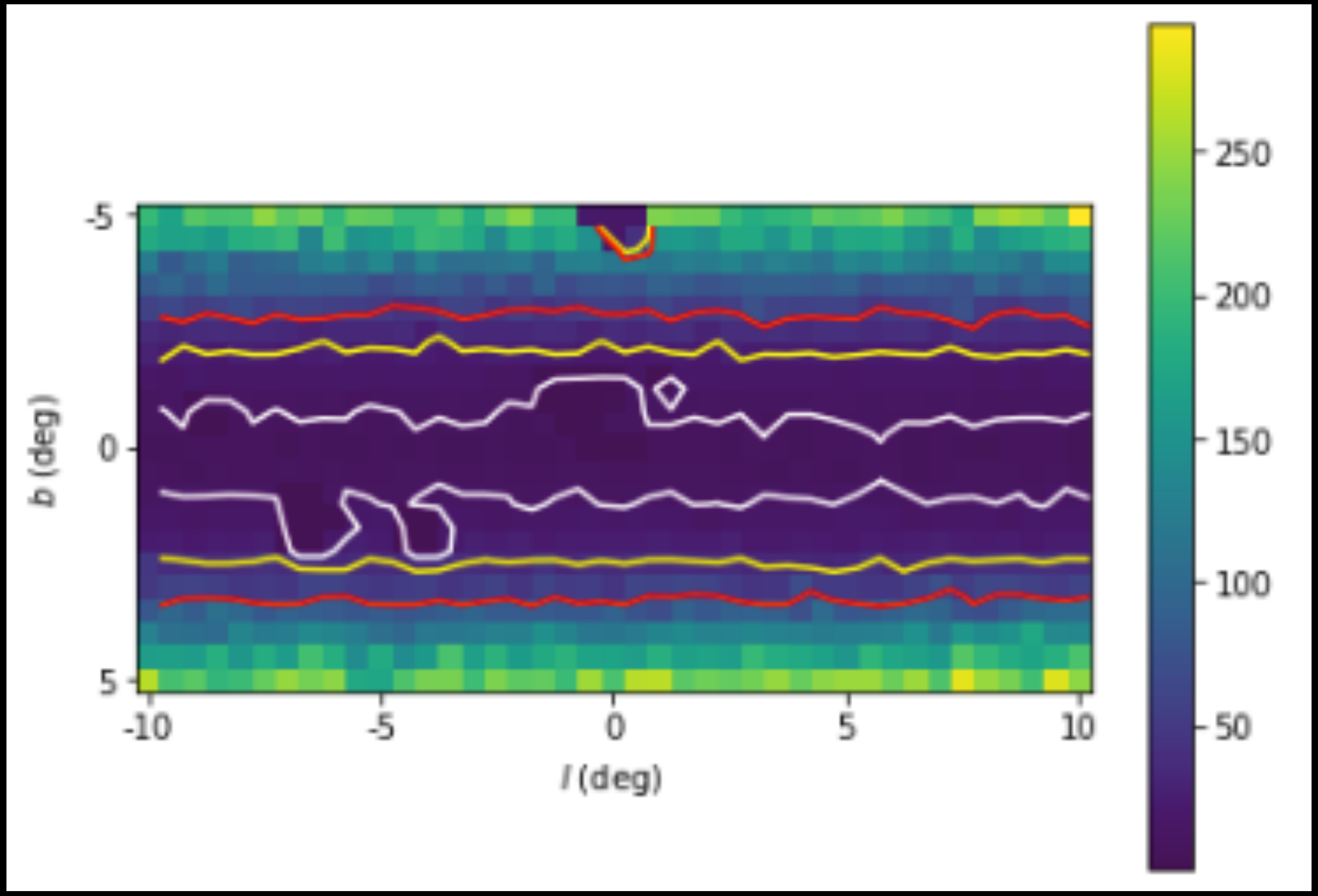
Threshold fit

Scintillation maps around the GC at C-band

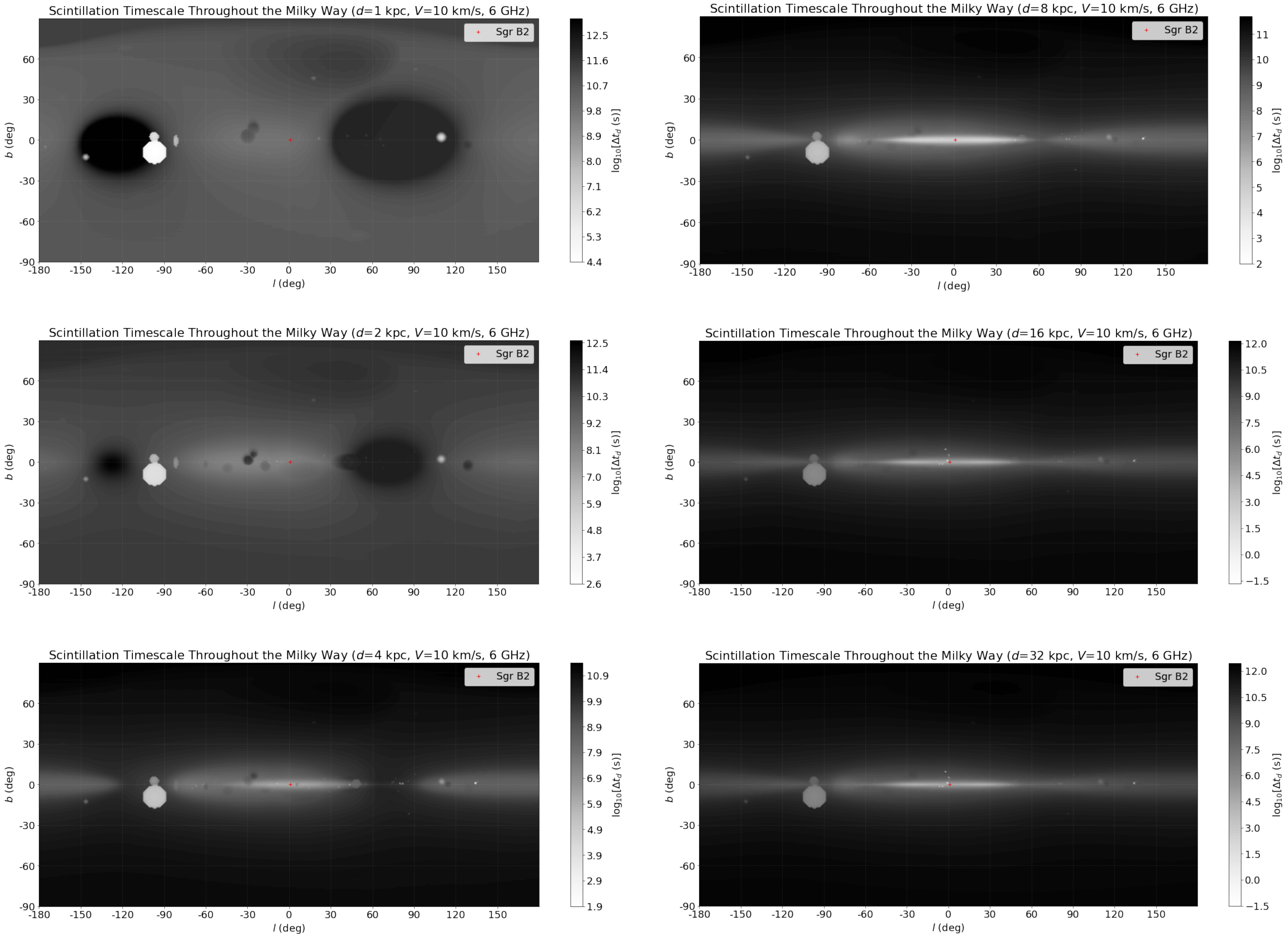
Median



Mode



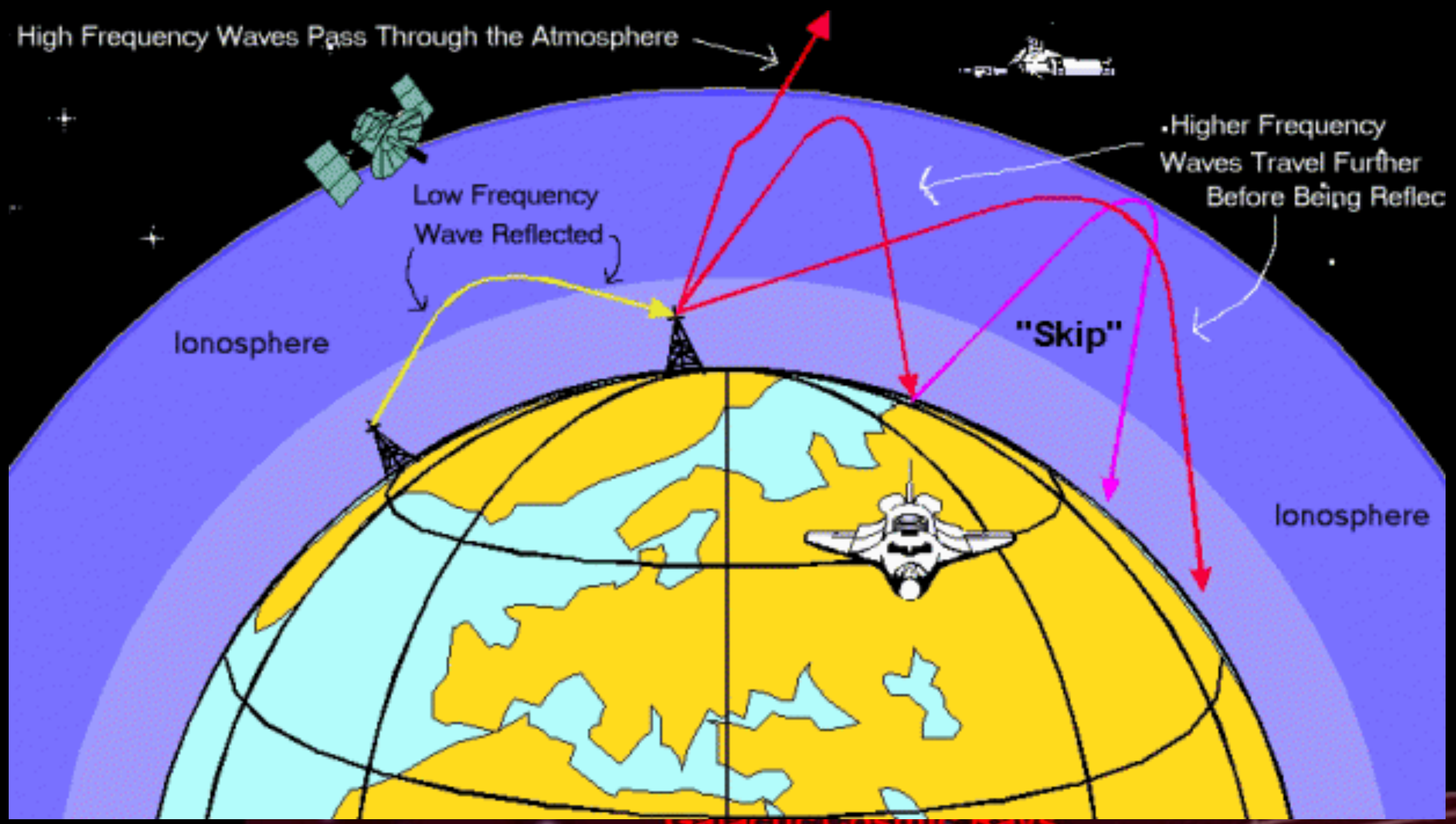
10 s, 30 s, 60 s

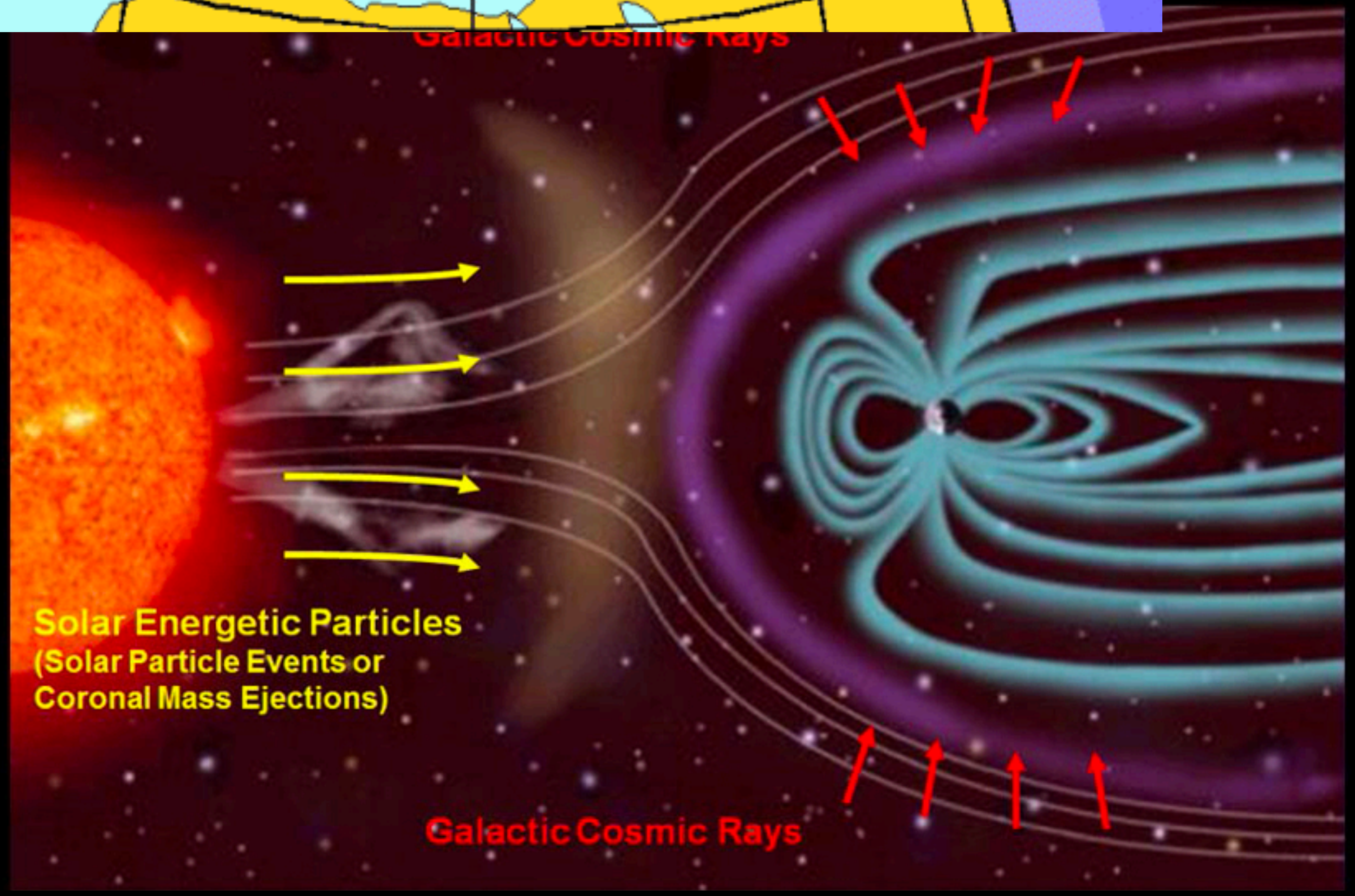


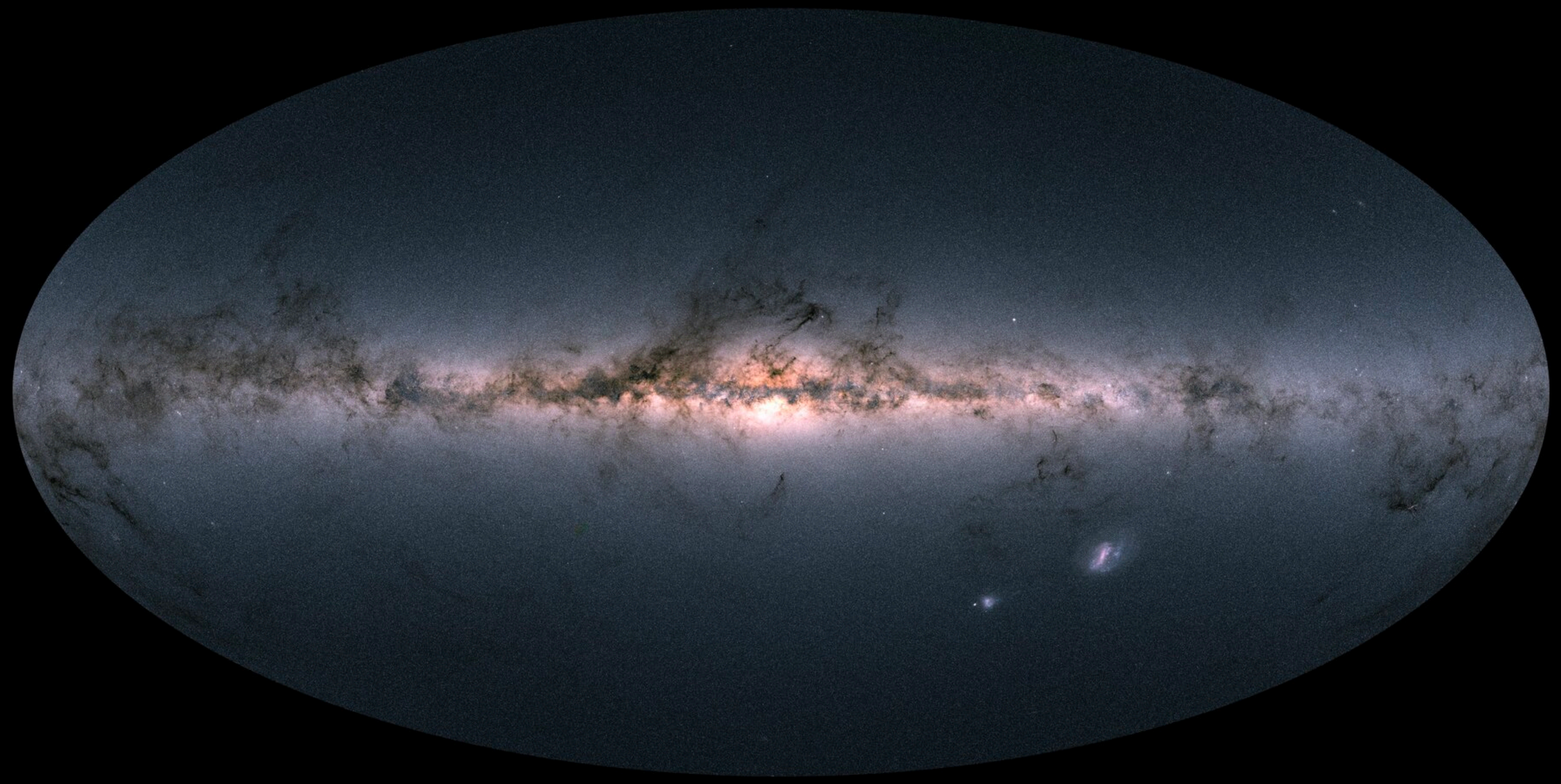
Scintillation Timescale Throughout the Milky Way (d=1 kpc, V=10 km/s, 6 GHz)
Scintillation Timescale Throughout the Milky Way (d=8 kpc, V=10 km/s, 6 GHz)
Scintillation Timescale Throughout the Milky Way (d=2 kpc, V=10 km/s, 6 GHz)
Scintillation Timescale Throughout the Milky Way (d=16 kpc, V=10 km/s, 6 GHz)
Scintillation Timescale Throughout the Milky Way (d=4 kpc, V=10 km/s, 6 GHz)
Scintillation Timescale Throughout the Milky Way (d=32 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150
-90 -60 -30 0 30 60
$\log_{10}[\Delta t_d$ (s)]
12.5 11.6 10.7 9.8 8.9 8.0 7.1 6.2 5.3 4.4
11 10 9 8 7 6 5 4 3 2
12.5 11.4 10.3 9.2 8.1 7.0 5.9 4.8 3.7 2.6
12.0 10.5 9.0 7.5 6.0 4.5 3.0 1.5 0.0 −1.5
10.9 9.9 8.9 7.9 6.9 5.9 4.9 3.9 2.9 1.9
12.0 10.5 9.0 7.5 6.0 4.5 3.0 1.5 0.0 −1.5

Scattering intensity

- Ionosphere – weak $m_d \ll 1$
- IPM – mostly weak
- ISM – can be strong! $m_d \approx 1$







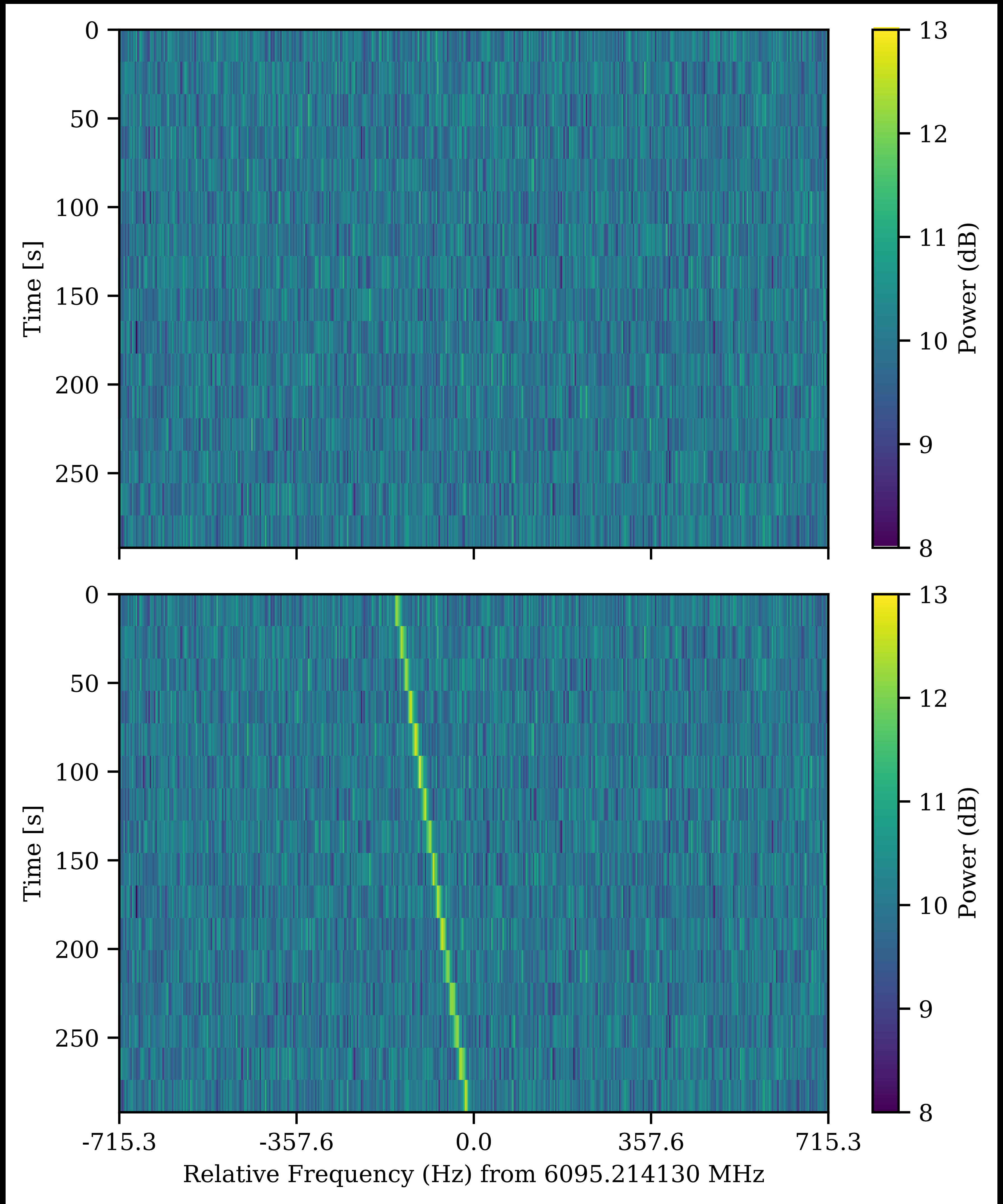
Setigen

- Python library for synthetic spectrogram and voltage data
- Specific focus on narrowband signal generation and injection

setigen Public

Python library for generating and injecting artificial narrow-band signals into radio frequency data

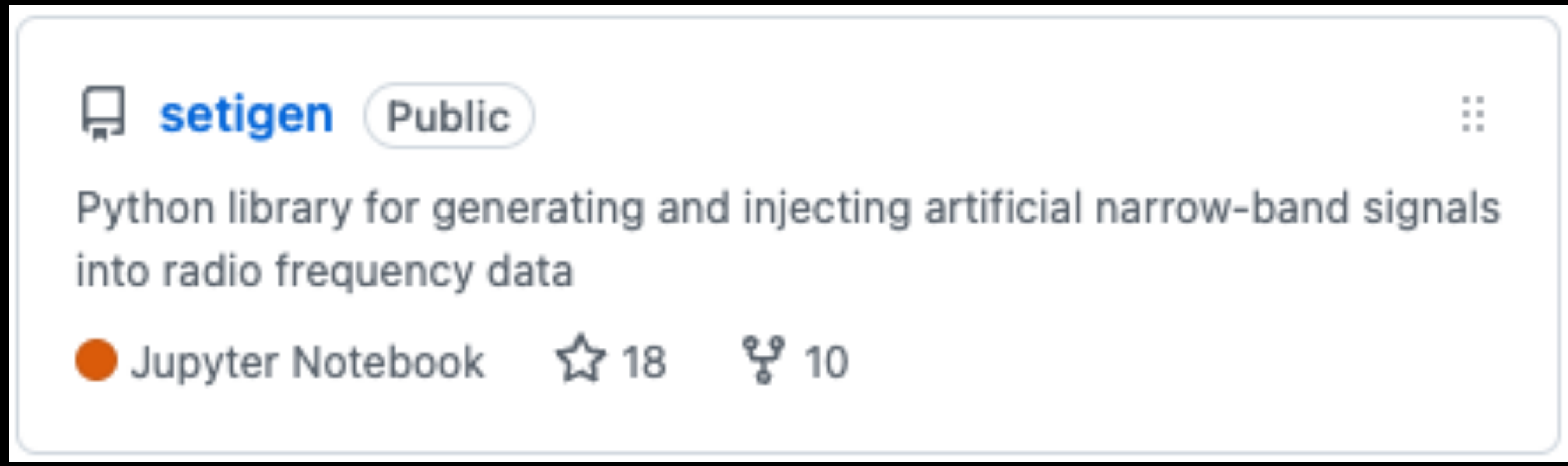
Jupyter Notebook ☆ 18 10

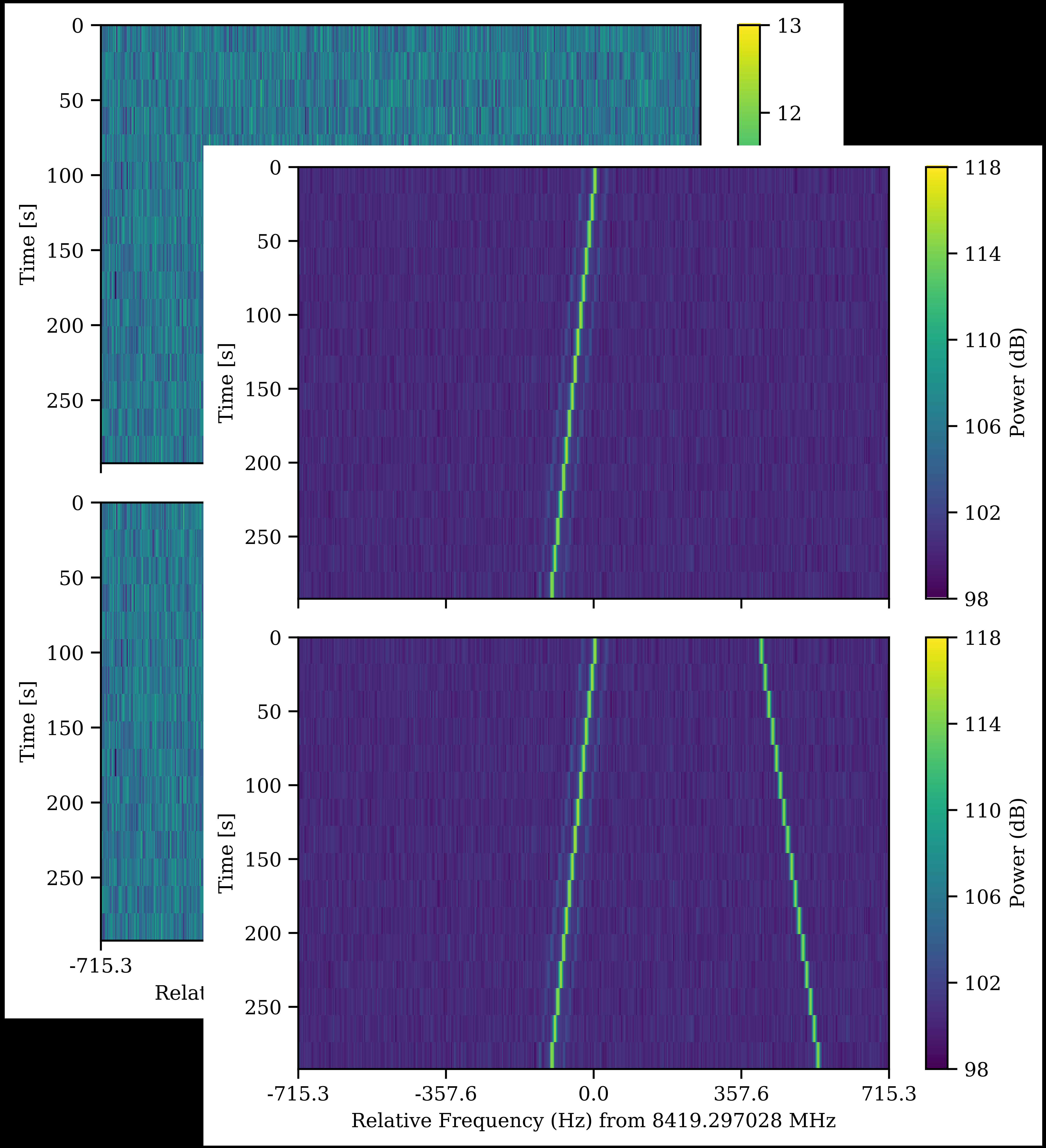


Brzycki et al. 2022, AJ

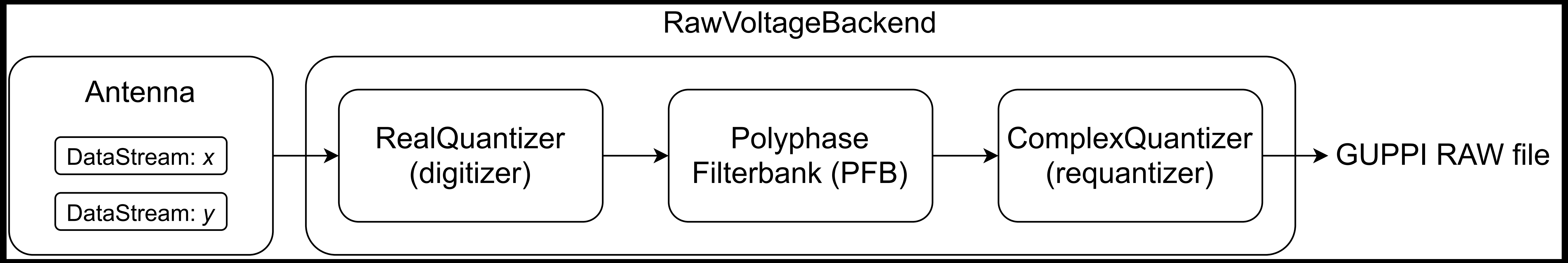
Setigen

- Python library for synthetic spectrogram and voltage data
- Specific focus on narrowband signal generation and injection

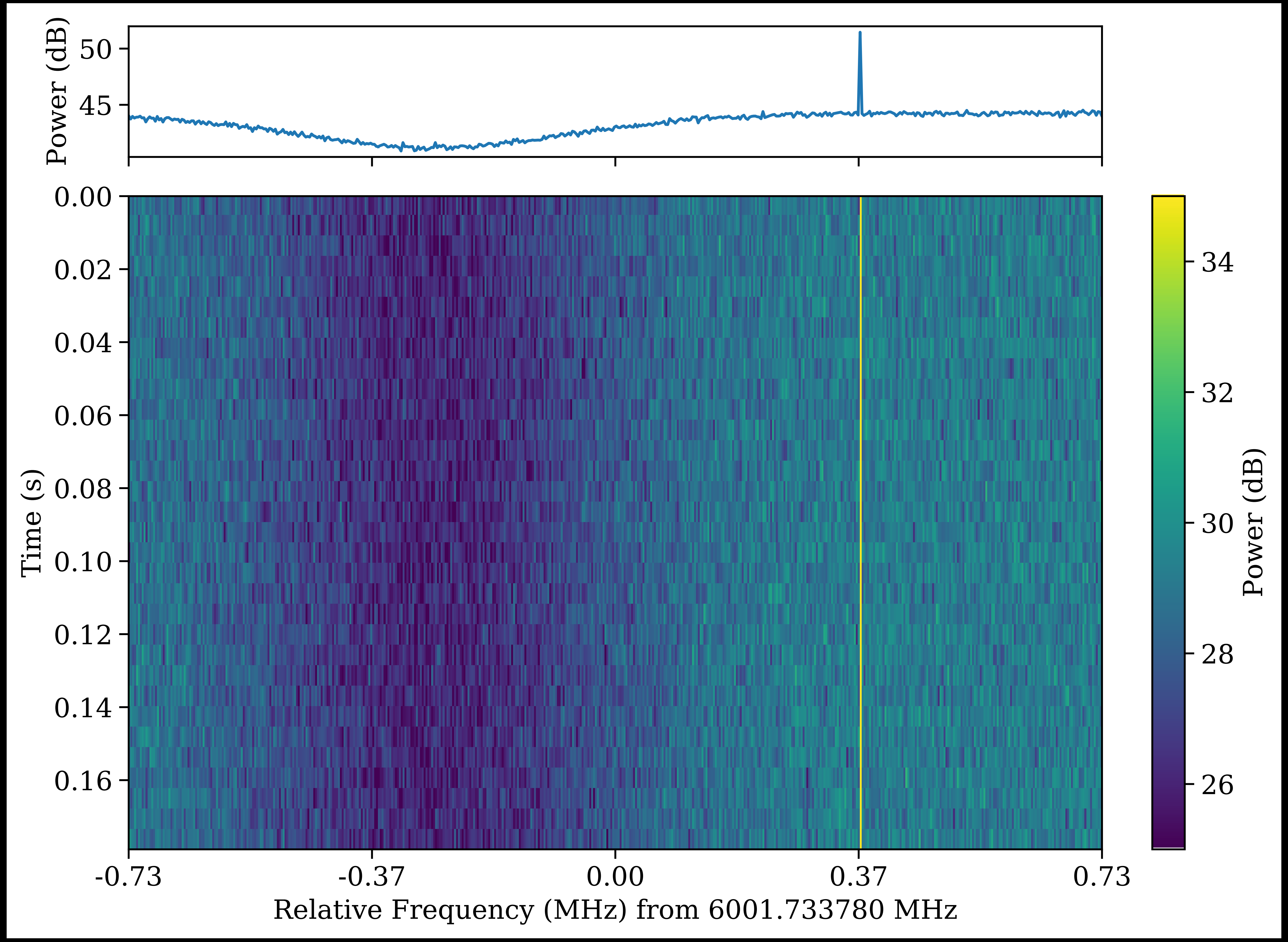




Brzycki et al. 2022, AJ

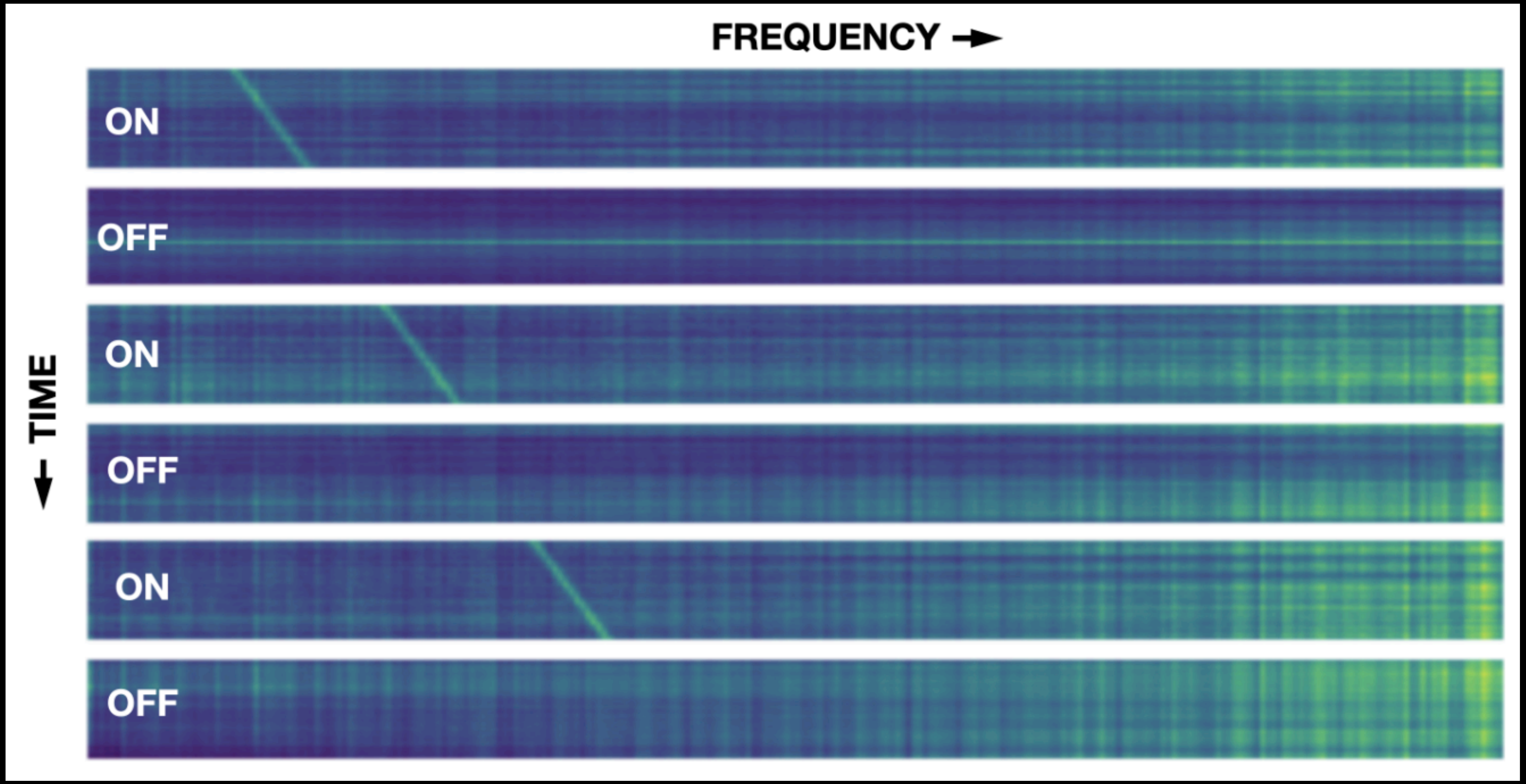


- Synthetic complex voltage data
- Simple models of backend components, such as a polyphase filterbank



Applications of Setigen beyond my research

- Injection – recovery testing
- ML dataset production (e.g. Kaggle)
- Multibeam search surveys
- Development of software for the Allen Telescope Array



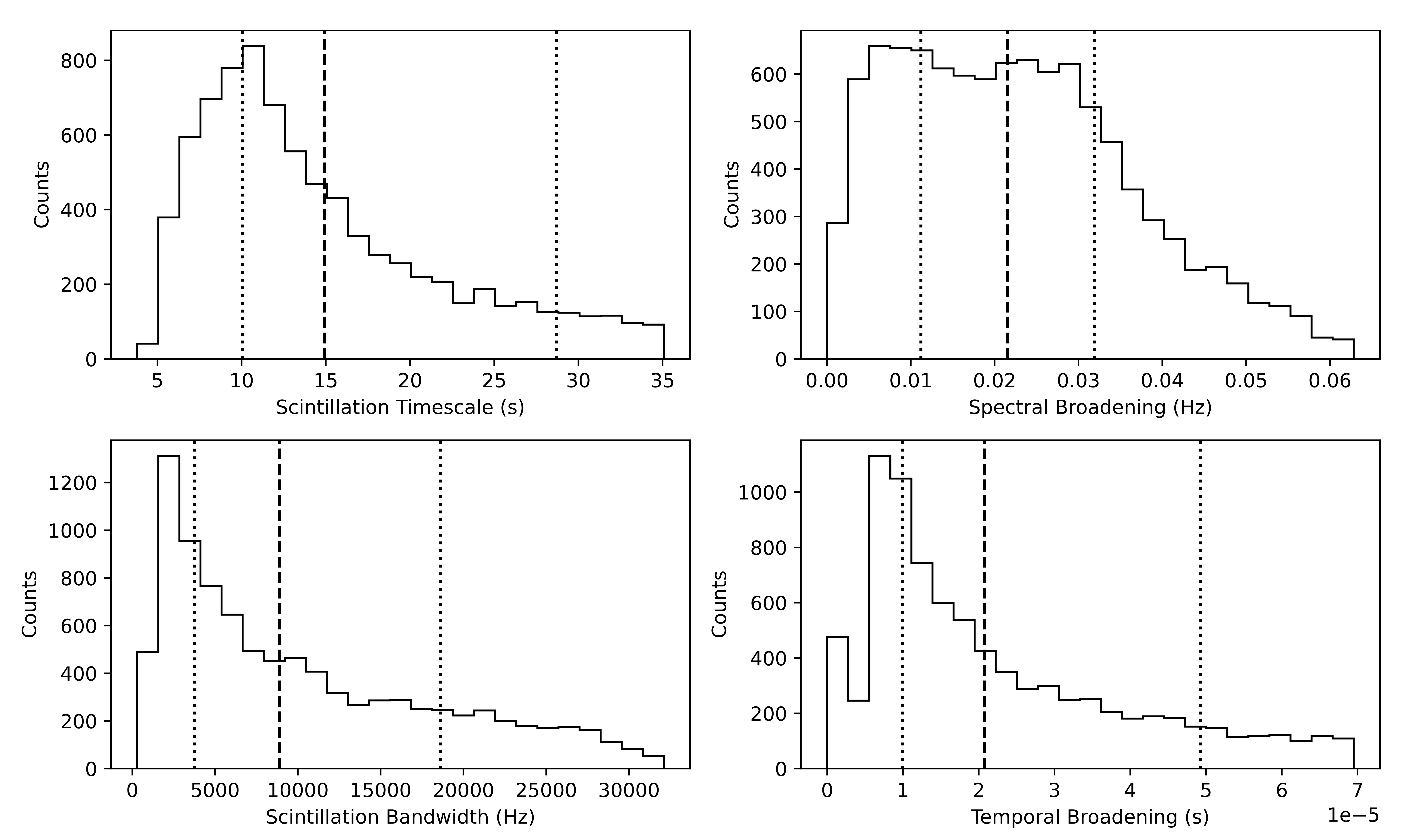
Breakthrough Listen x Kaggle 2021

C-band

(l, b) = (1, 0)

Inter-quartile

Media



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BREAKTHROUGH LISTEN

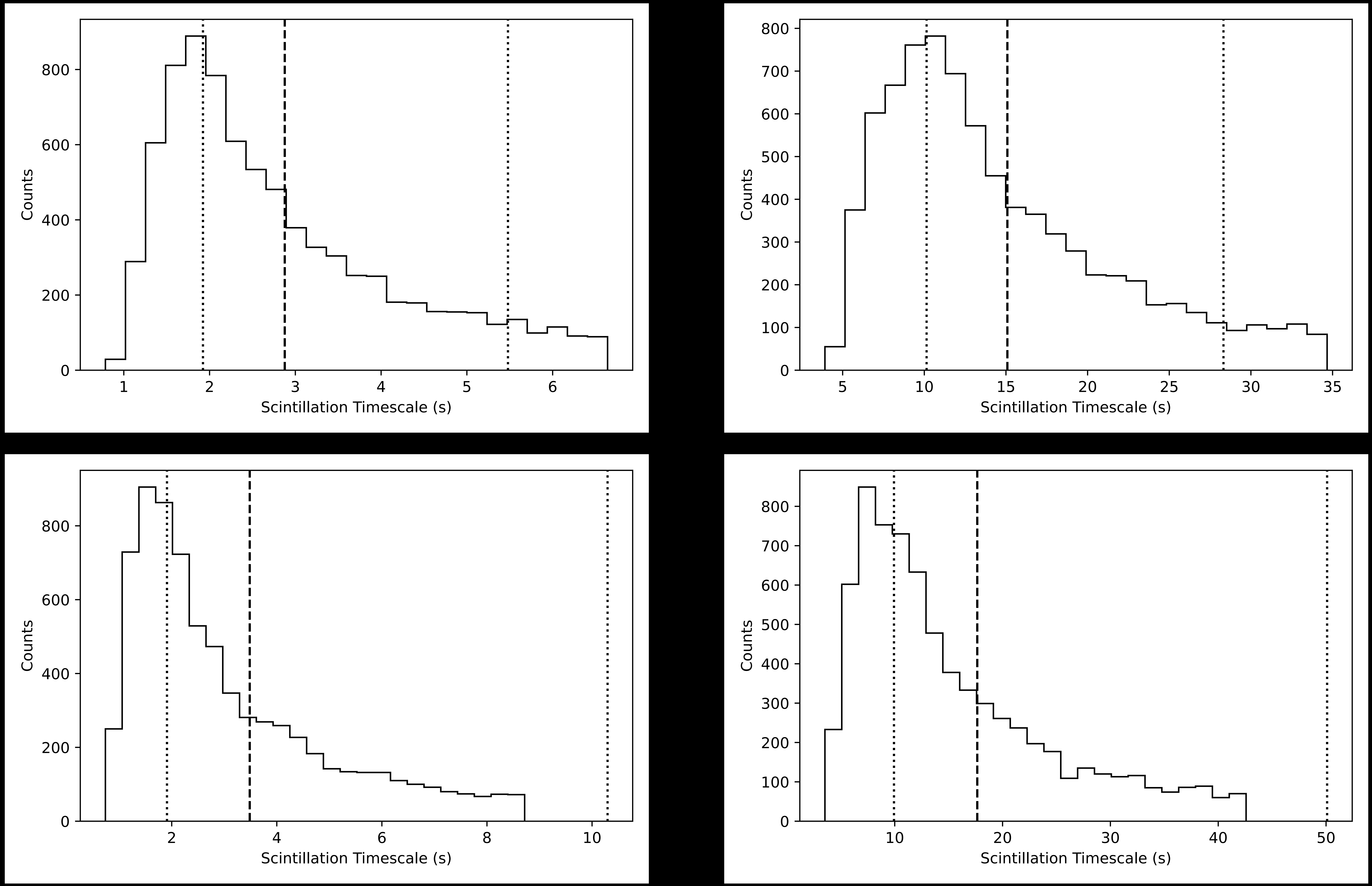
Monte Carlo-sampled timescales

L band

C band

Density

Uniform



Distance sampling

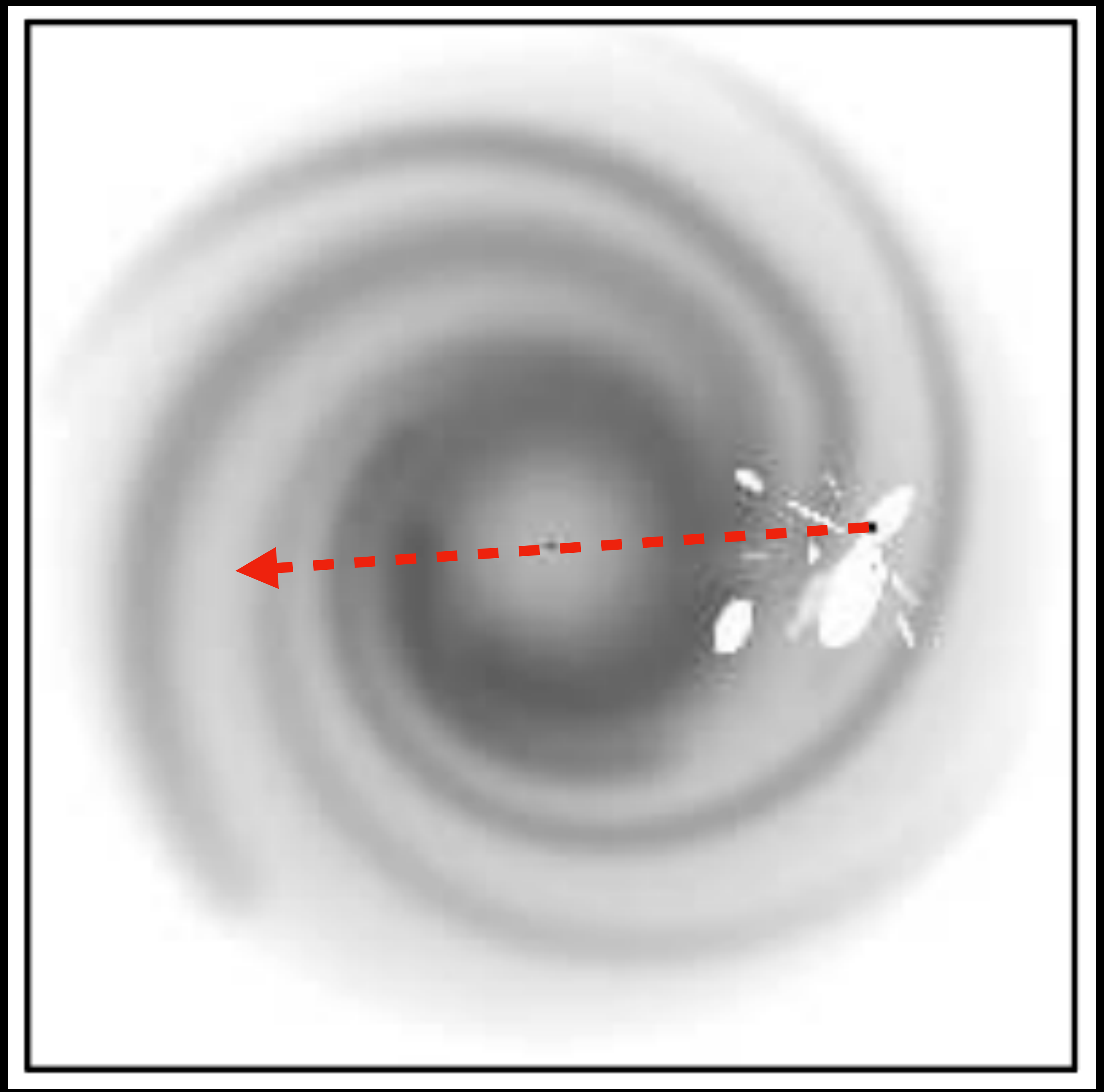
Statistics at different bands

(l, b) = (1, 0)

Band	Frequency (GHz)	Median (s)	IQR (s)	Mode (s)
LOFAR	0.110 – 0.240	0.22	0.14 – 0.41	0.14
L	1.1 – 1.9	2.9	1.9 – 5.6	1.9
S	1.8 – 2.8	4.8	3.3 – 9.0	3.1
C	3.95 – 8	15	10 – 28	11
X	8 – 11.6	28	19 – 52	16

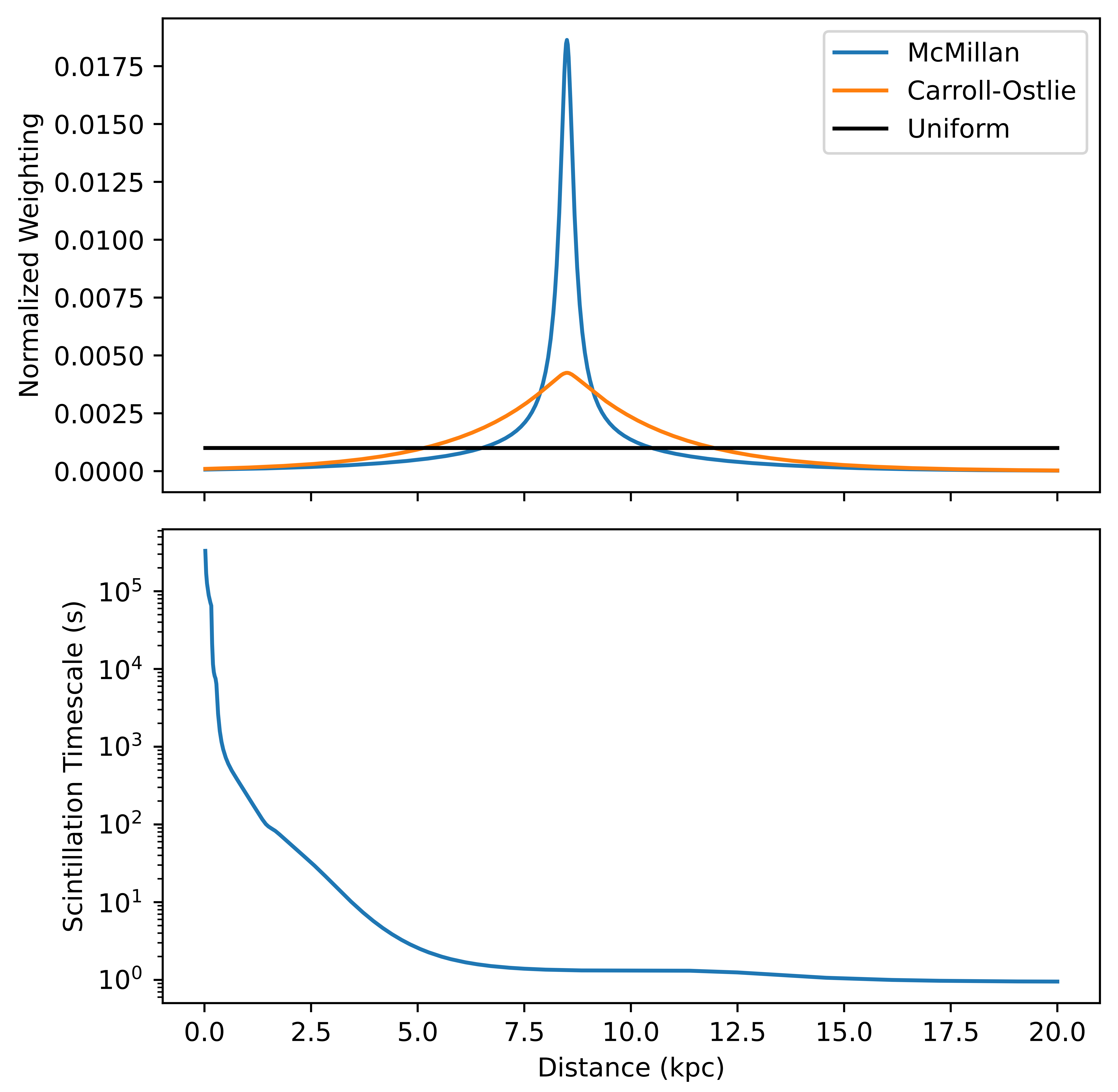
$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$

Density-based sampling



Cordes & Lazio 2002

(l, b) = (1, 0)



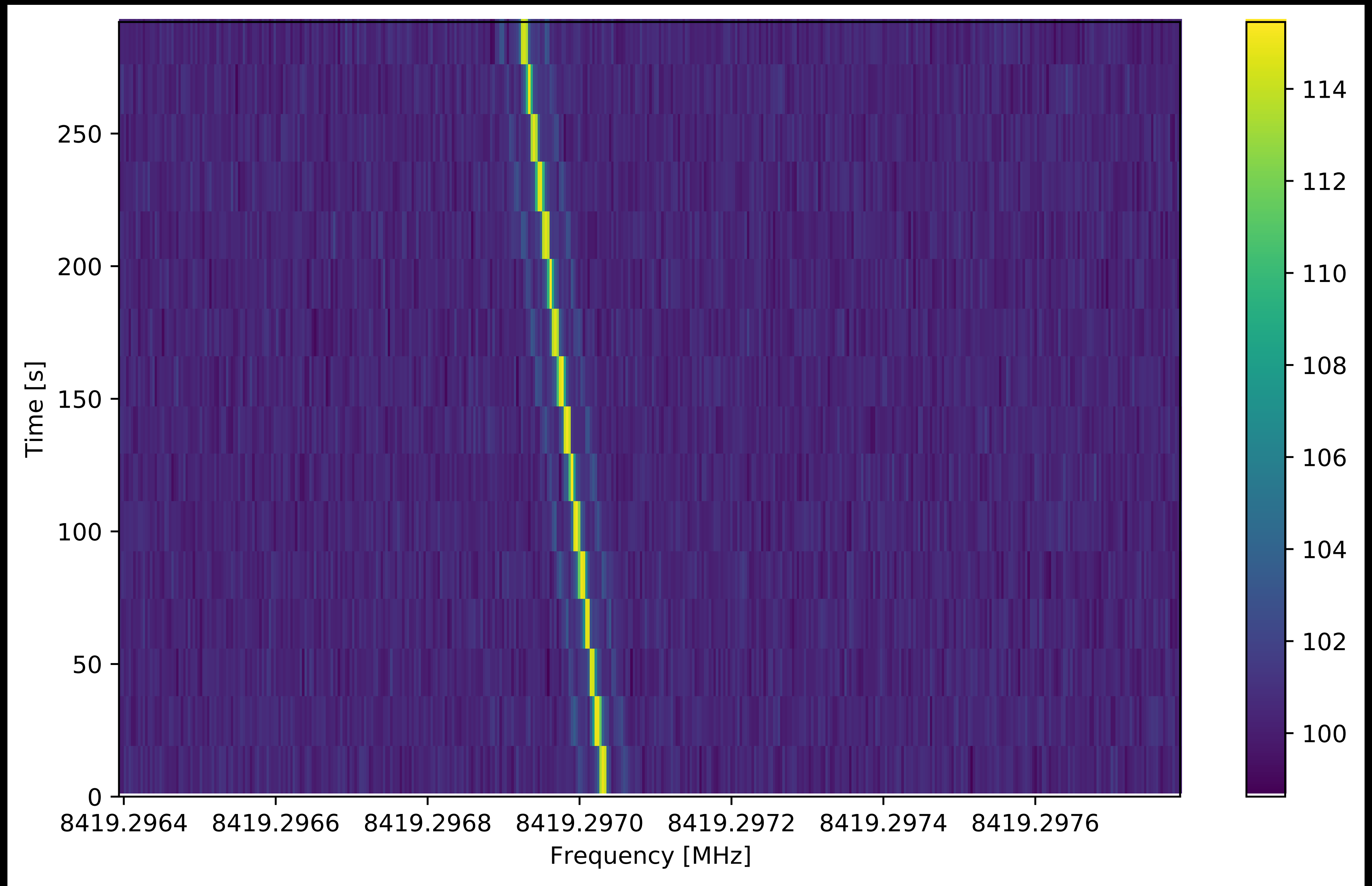
McMillan 2017, Gowanlock et al. 2011, Carroll & Ostlie 2007

What would strongly scattered signals look like?

- Temporal scintillation
- Spectral broadening
- Pulse broadening
- Spectral de-correlation

What would strongly scattered signals look like?

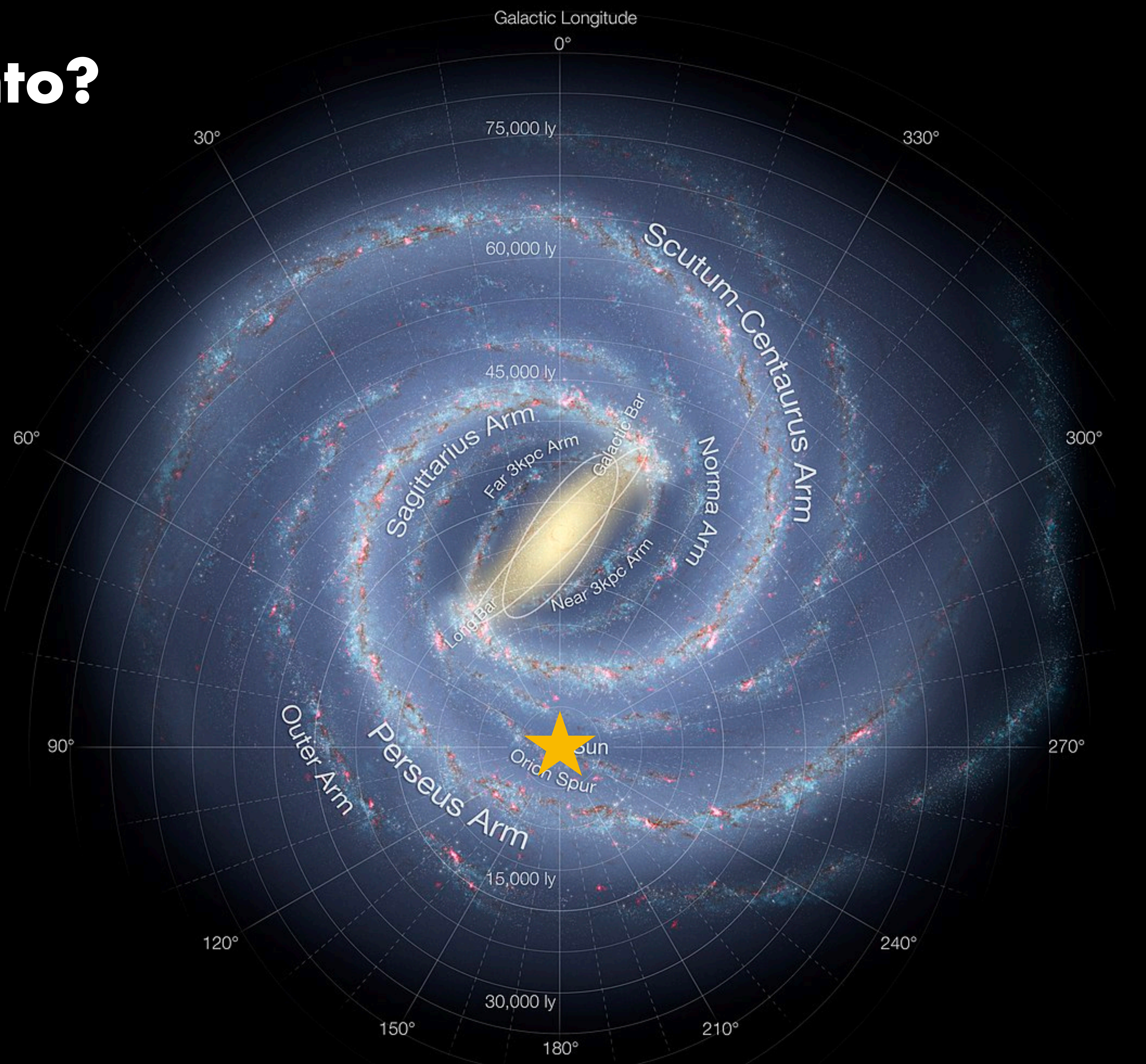
- Assuming a 100% duty-cycle narrowband transmitter



- Temporal scintillation
- ~~Spectral broadening~~
- ~~Pulse broadening~~
- ~~Spectral de-correlation~~

Why is this worth looking into?

- Astrophysical modulation as a filter for technosignature candidates
- Looking towards the Galactic Center is well motivated by SETI
- Could provide a framework for using more of the actual signals during narrowband analysis



NASA/JPL

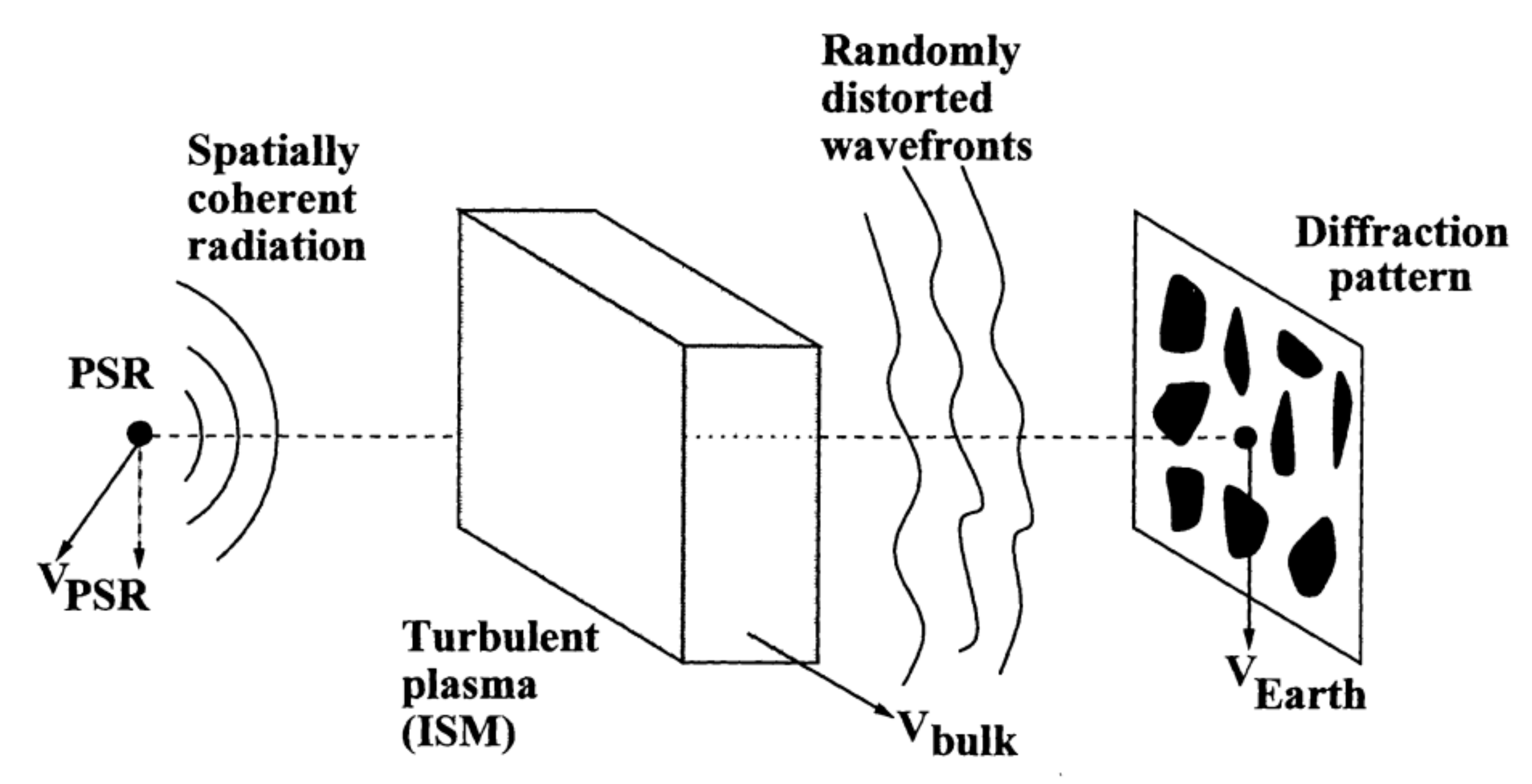
We focus on so-called diffractive scintillations

- Electron density fluctuations give rise to phase fluctuations

- Multi-path propagation

- Interference pattern with characteristic spatial and spectral scales

- Can lead to 100% intensity modulation on characteristic temporal scales Δt_d



Cordes 2002

Parameter space exploration of scattering parameters

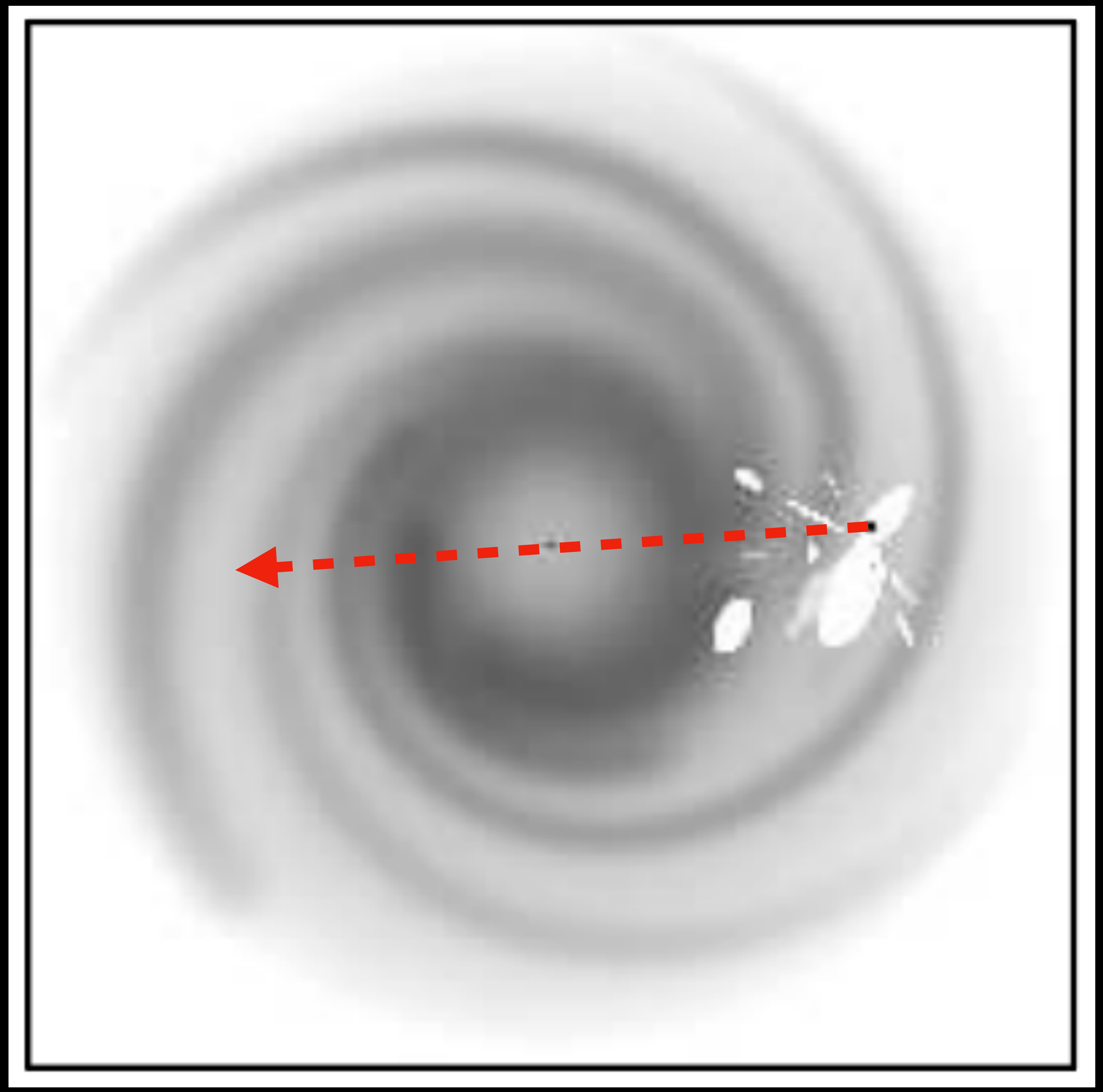
- A priori, we do not know:
  - Sky direction
  - Frequency
  - Distance
  - Transverse velocity

Monte Carlo sampling!

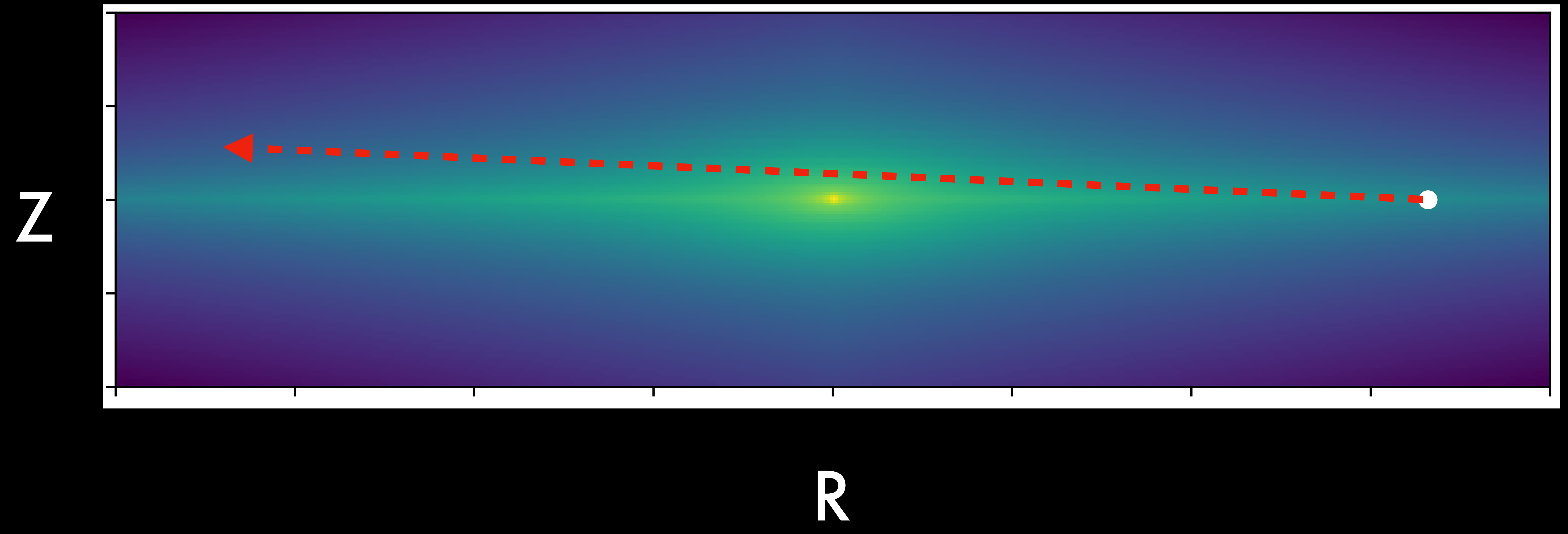
$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$

- Sky direction → Chosen parameter
- Frequency → Uniform sampling within chosen band
- Distance → Uniform or density based sampling
- Transverse velocity → Uniform sampling

Density-based sampling



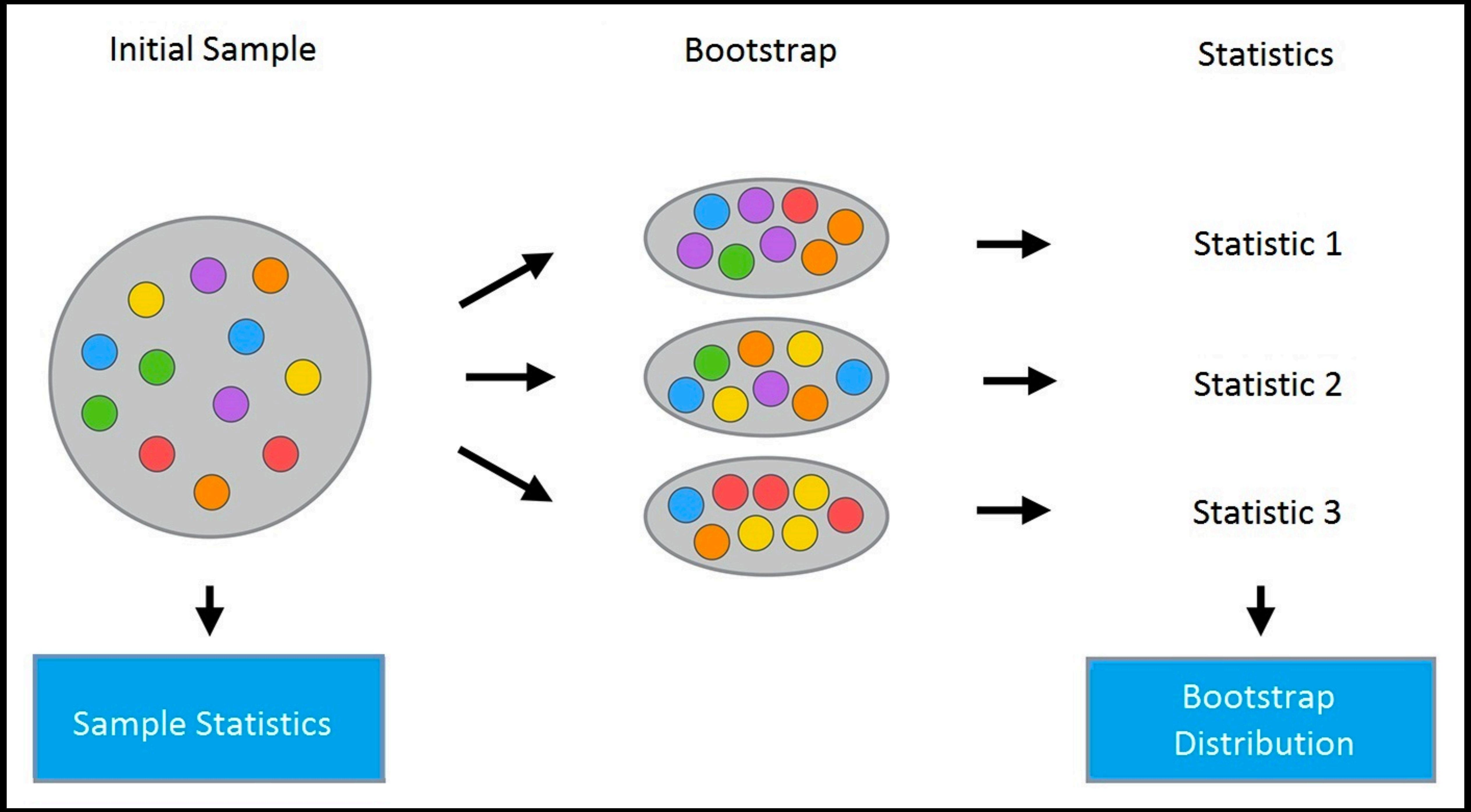
Cordes & Lazio 2002



McMillan 2017, Gowanlock et al. 2011, Carroll & Ostlie 2007

Low sample regime

- Spread of values around the asymptotic "truth"
- Both correlated and uncorrelated samples within the same observation
- How can we evaluate this?



Kaggle

Quick way to produce synthetic data with asymptotic statistics

- (Cario & Nelson 1996) The ARTA random process:
  - Matches a target intensity distribution
  - Matches a target autocorrelation structure (with custom asymptotic precision)

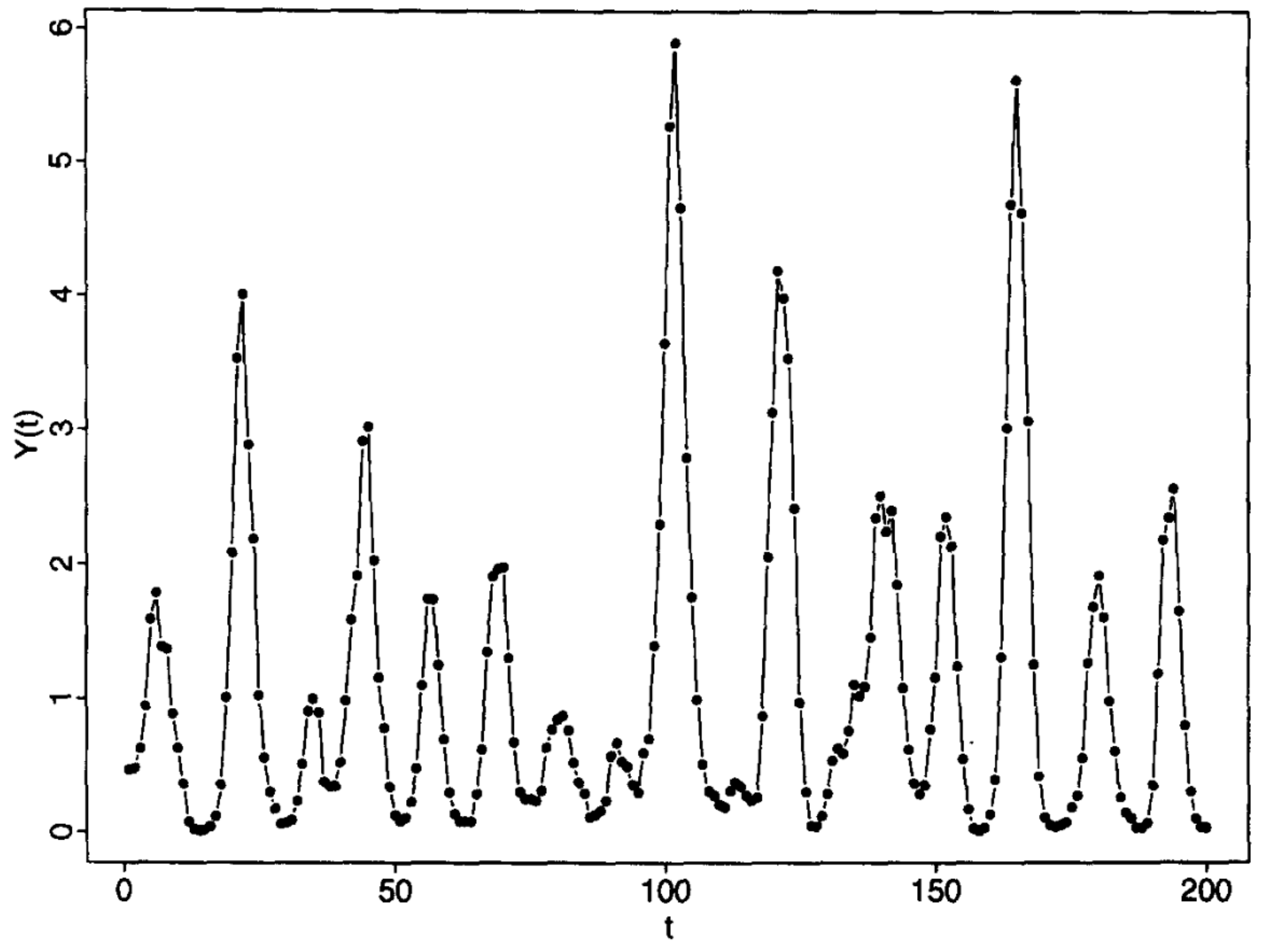
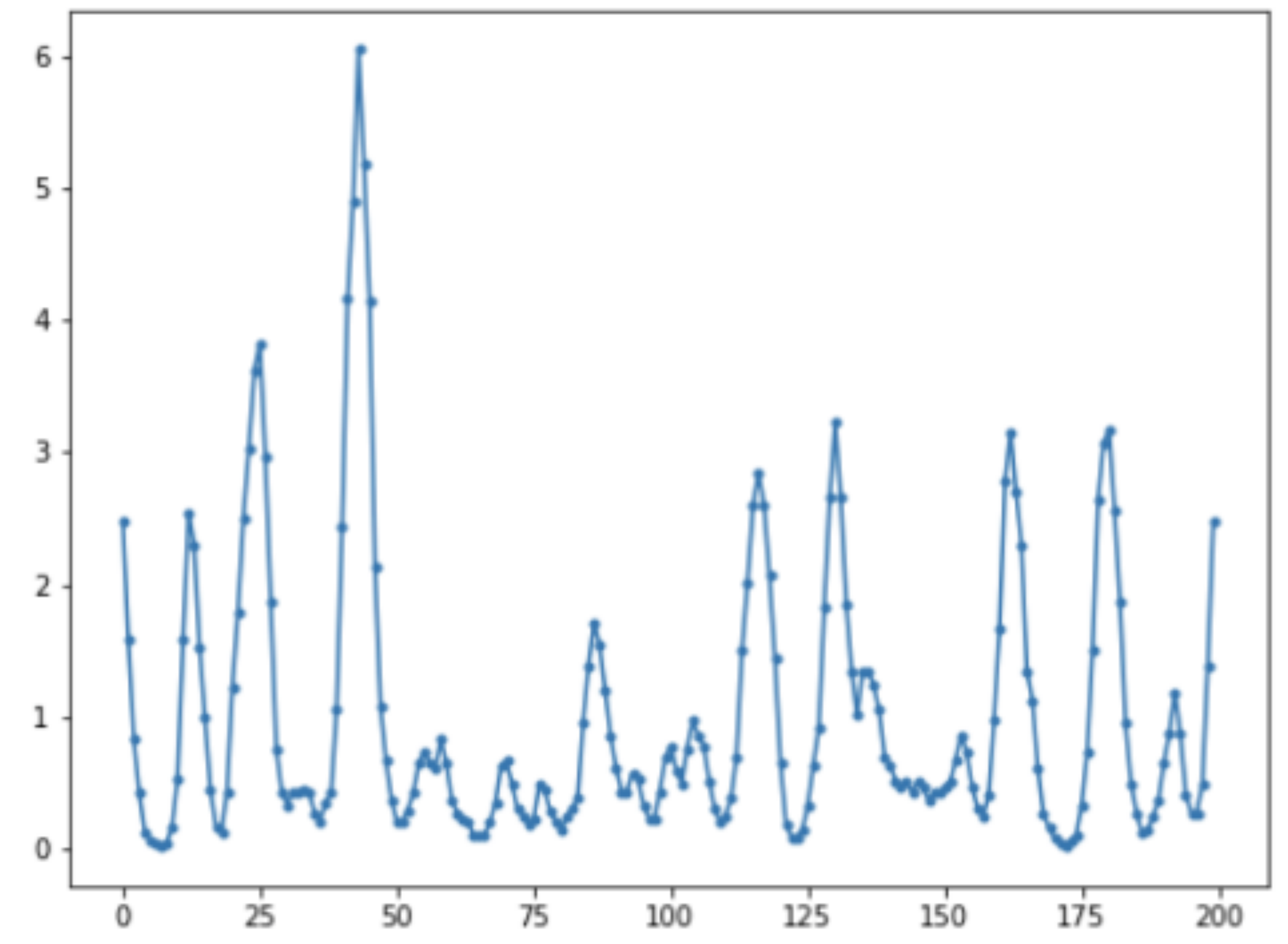


Fig. 1. Sample path of an ARTA process with exponential marginals and autocorrelations $\rho_1 = 0.9$ and $\rho_2 = 0.6$.

Cario & Nelson 1996



Our implementation