

BREAKTHROUGH LISTEN

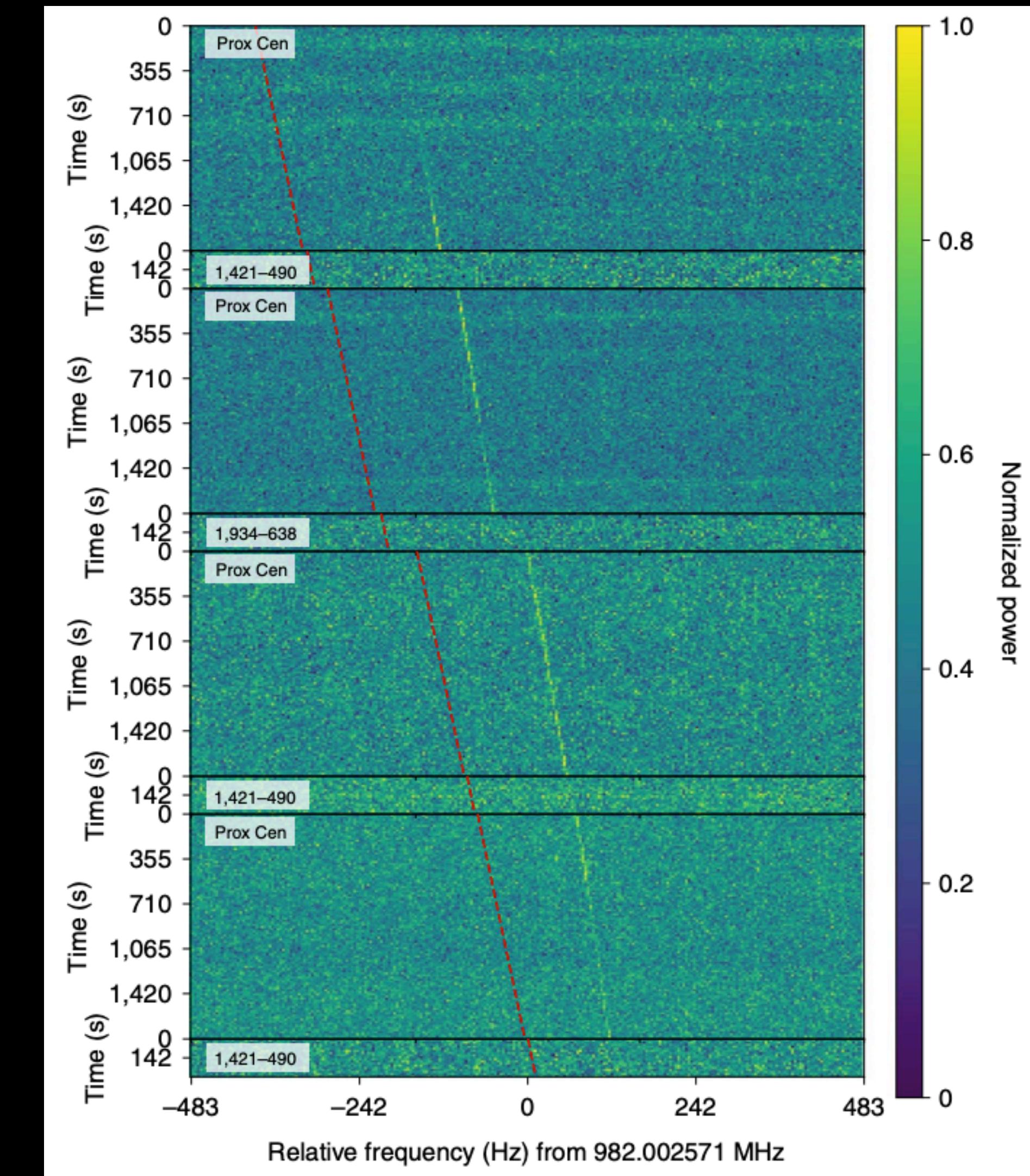
Astrophysical Effects on Narrowband Signals

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UNIVERSITY OF CALIFORNIA BERKELEY
BREAKTHROUGH ADVISORY, JUNE 21, 2022



Candidate identification and differentiation

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



Smith et al. 2021

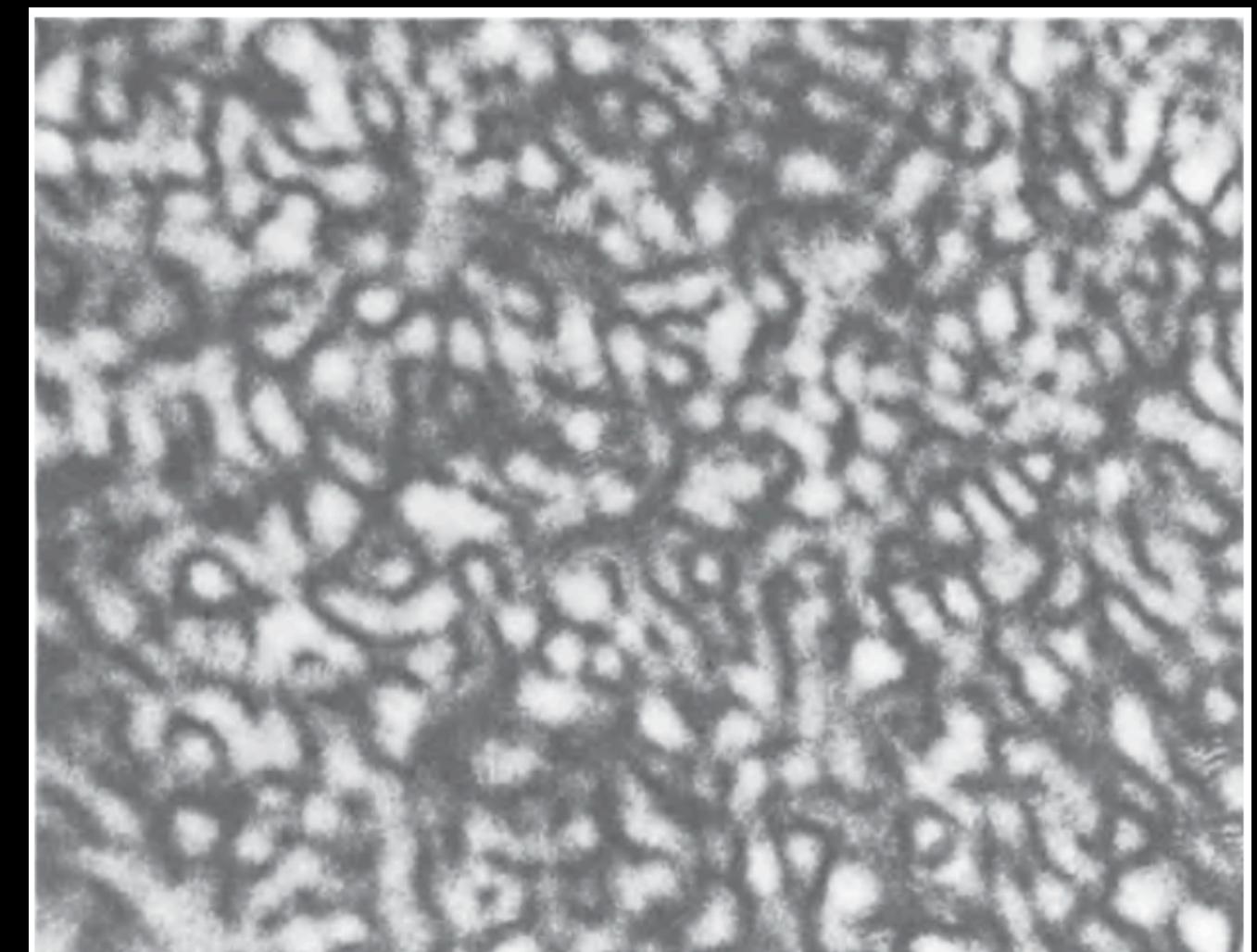
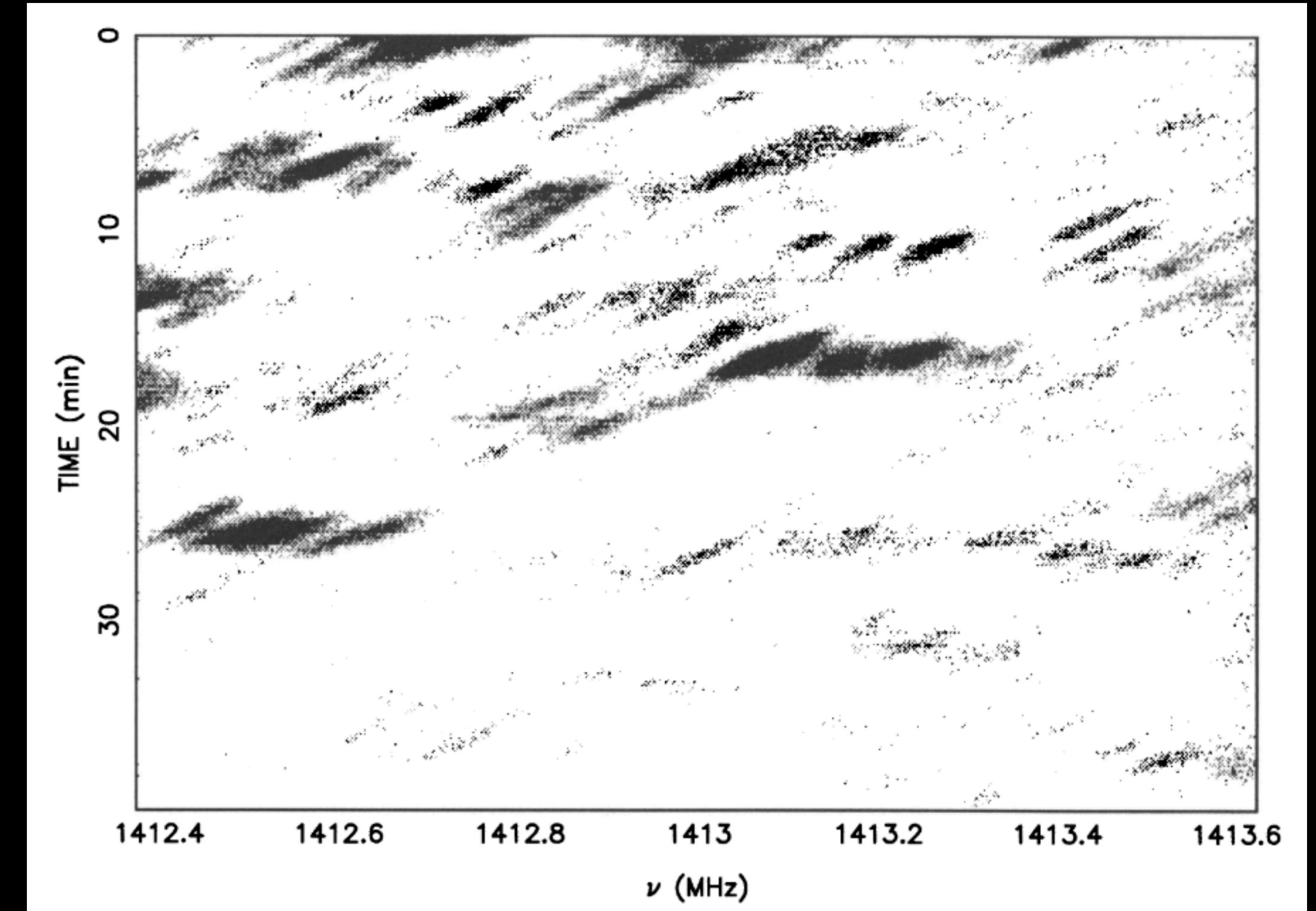
Can we use astrophysical phenomena to discriminate technosignatures from RFI?



ESA

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
BREAKTHROUGH
LISTEN

Scattering and SETI research

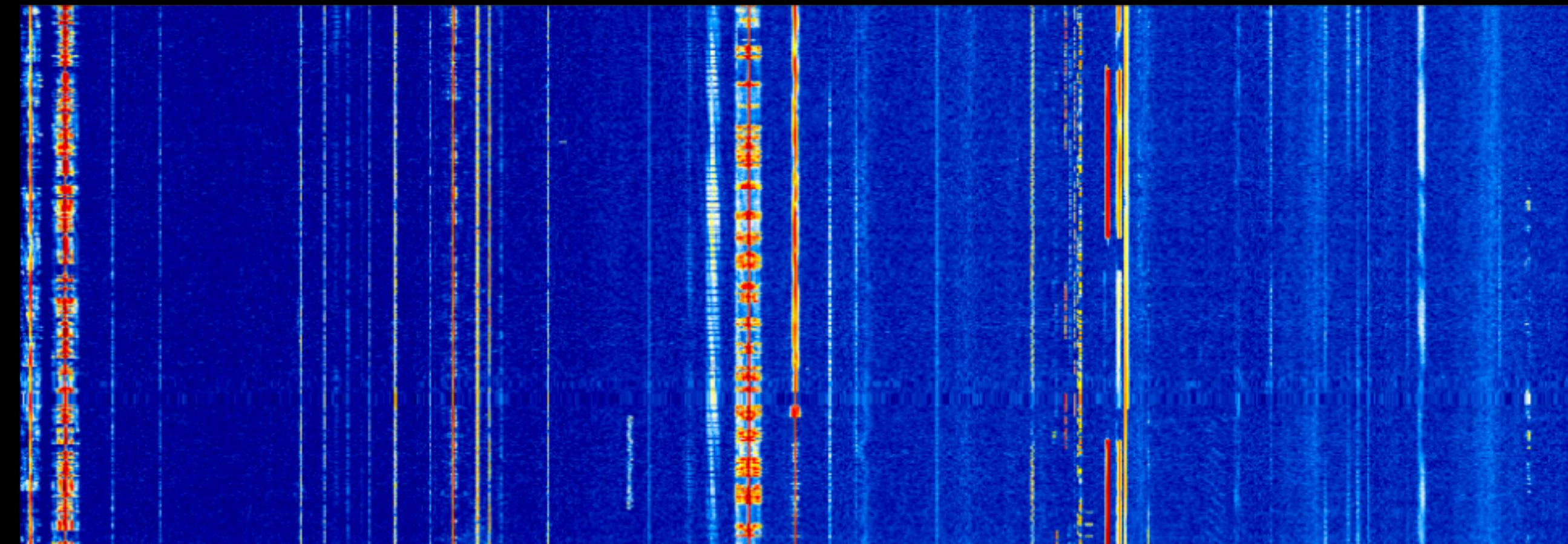
INTERSTELLAR SCATTERING EFFECTS ON THE DETECTION OF NARROW-BAND SIGNALS

JAMES M. CORDES AND T. JOSEPH LAZIO

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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

What would strongly scintillated signals look like?

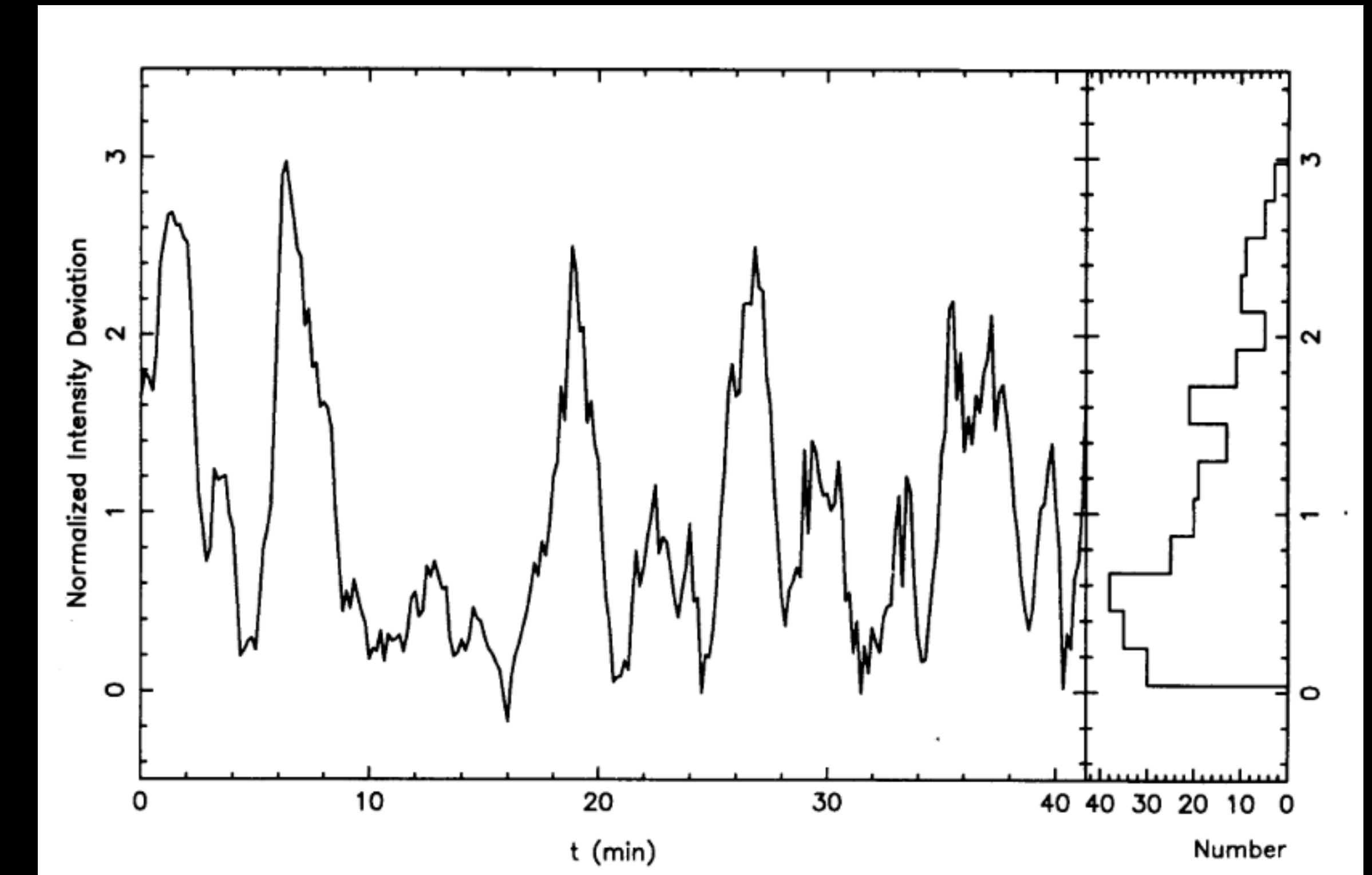
- Exponential intensity distribution

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

- Near Gaussian auto-correlation (ACF), with characteristic timescale

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

Assuming a 100% duty-cycle narrowband transmitter



Cordes & Lazio 1991;
Cordes, Lazio, Sagan 1997

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?

Estimating scattering strength

- NE2001 model estimates scattering parameters

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

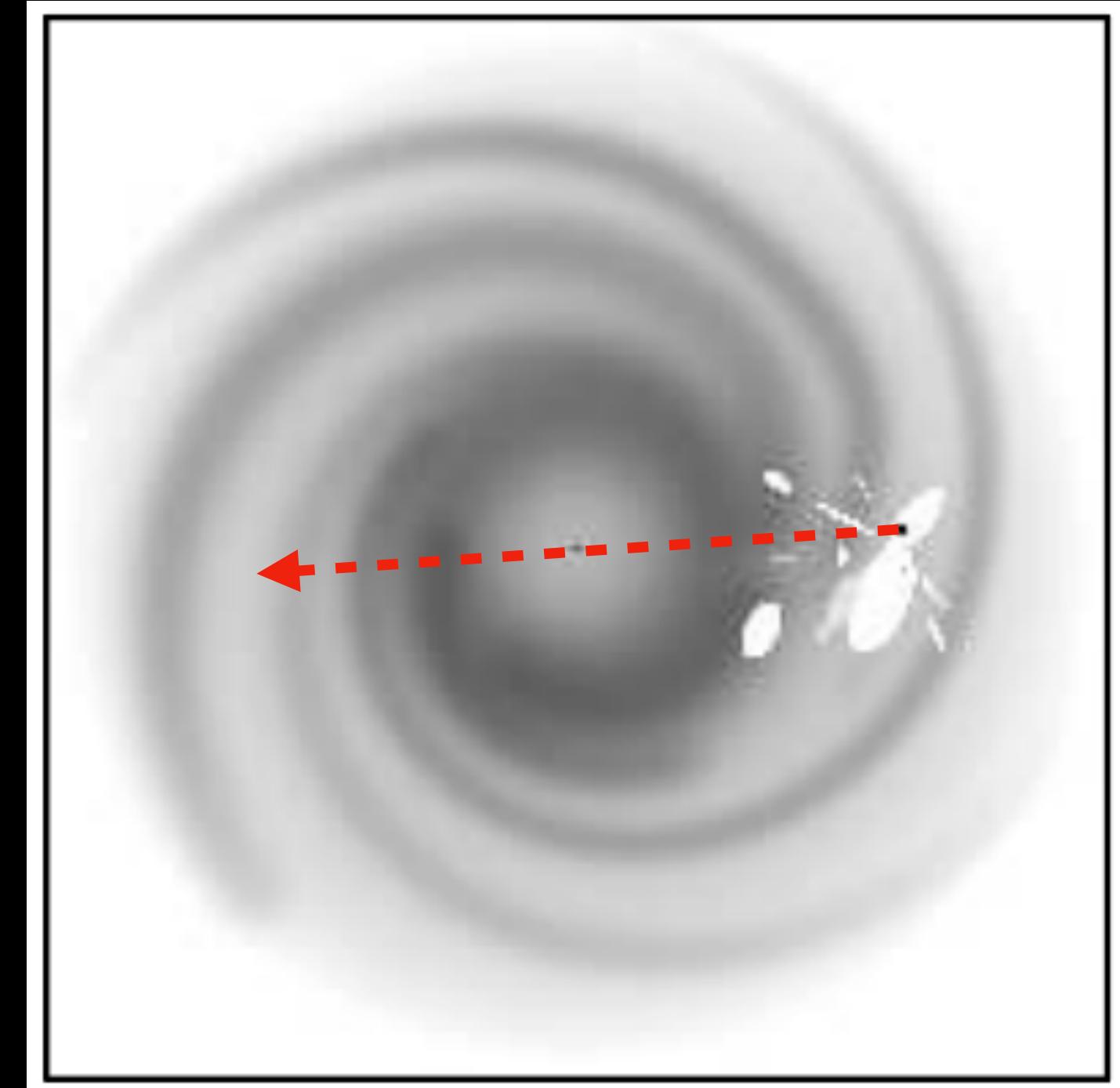
$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$

- We use Monte Carlo sampling for unknown parameters

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

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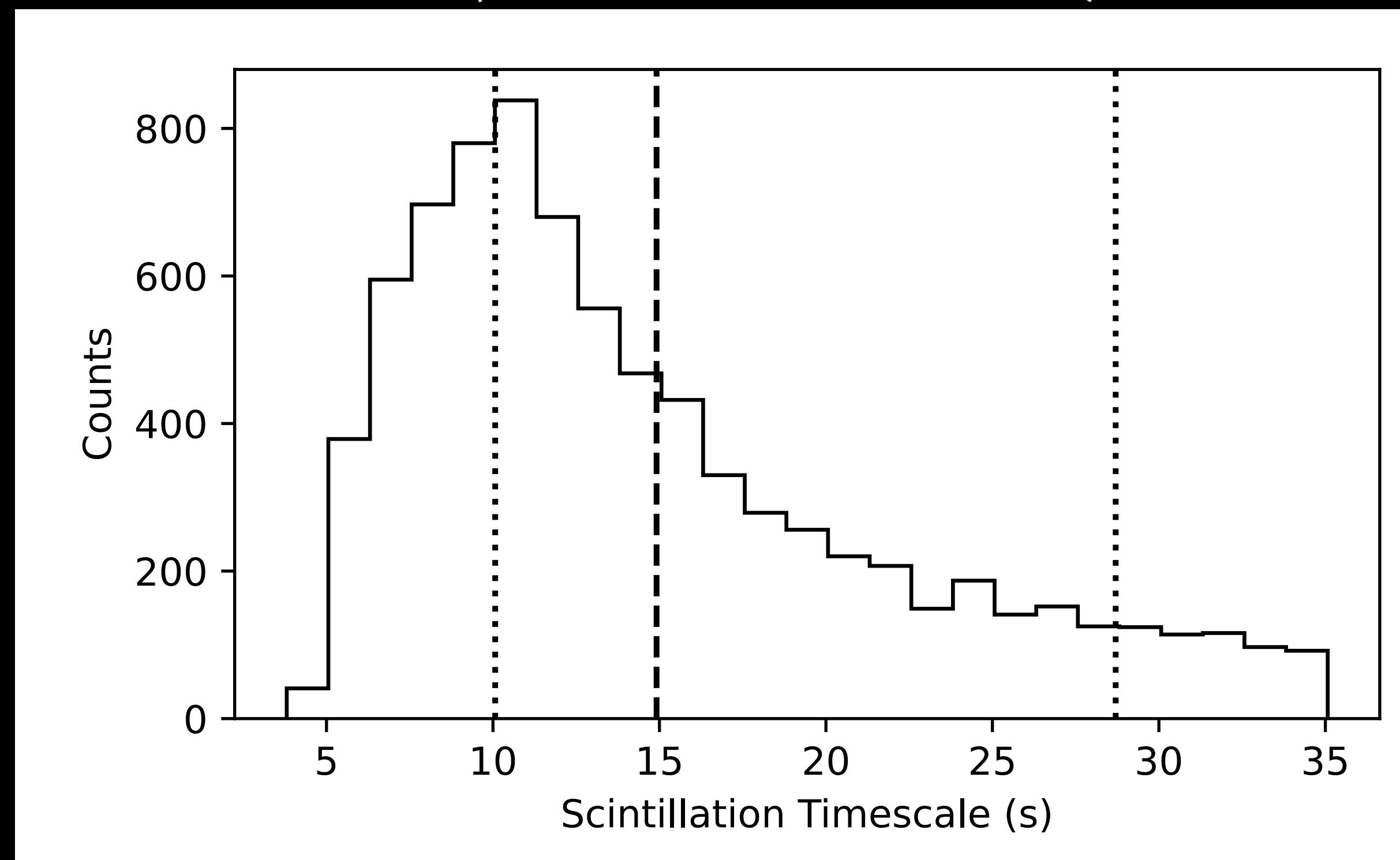


C-band

$(l, b) = (1, 0)$

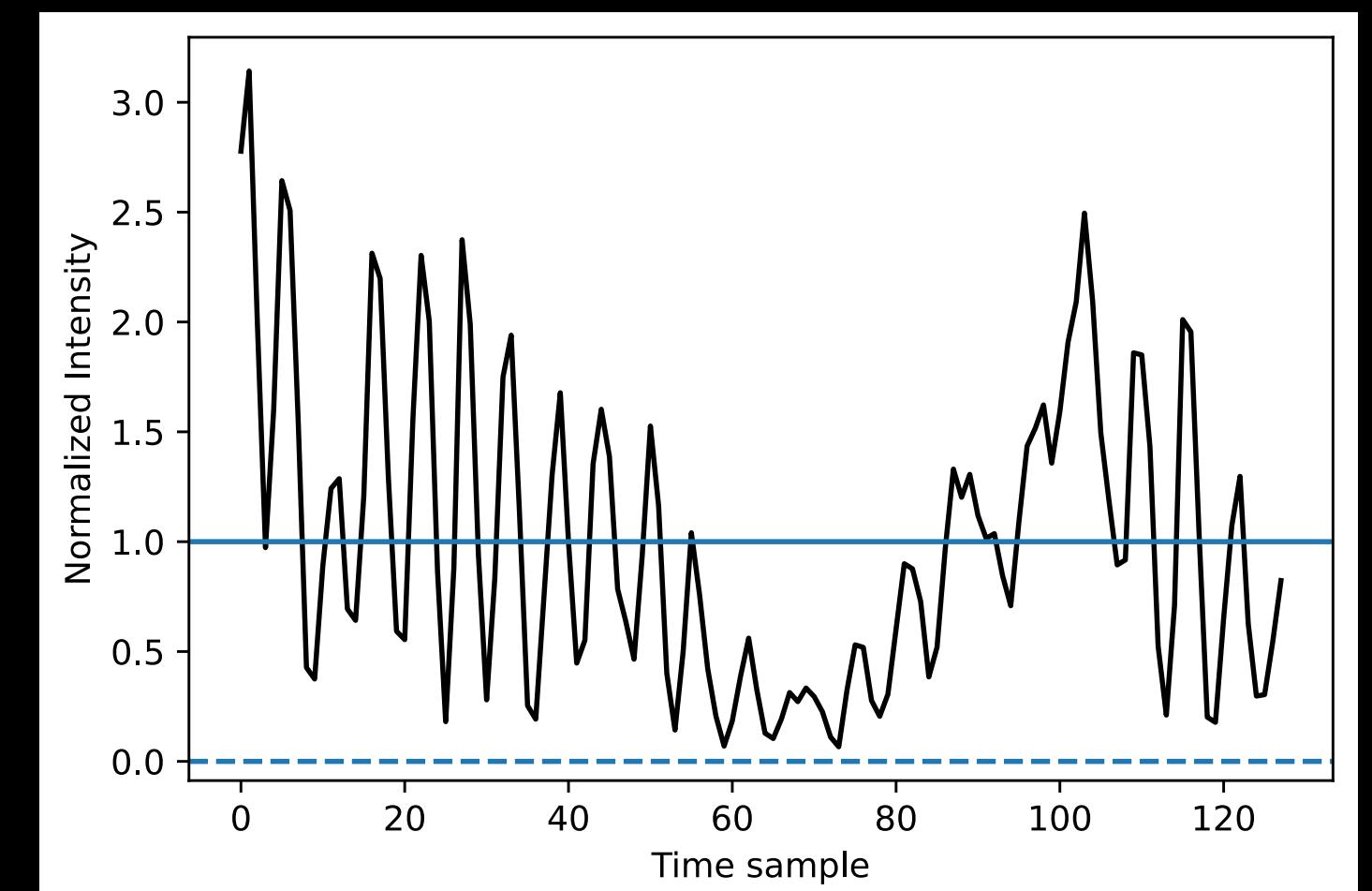
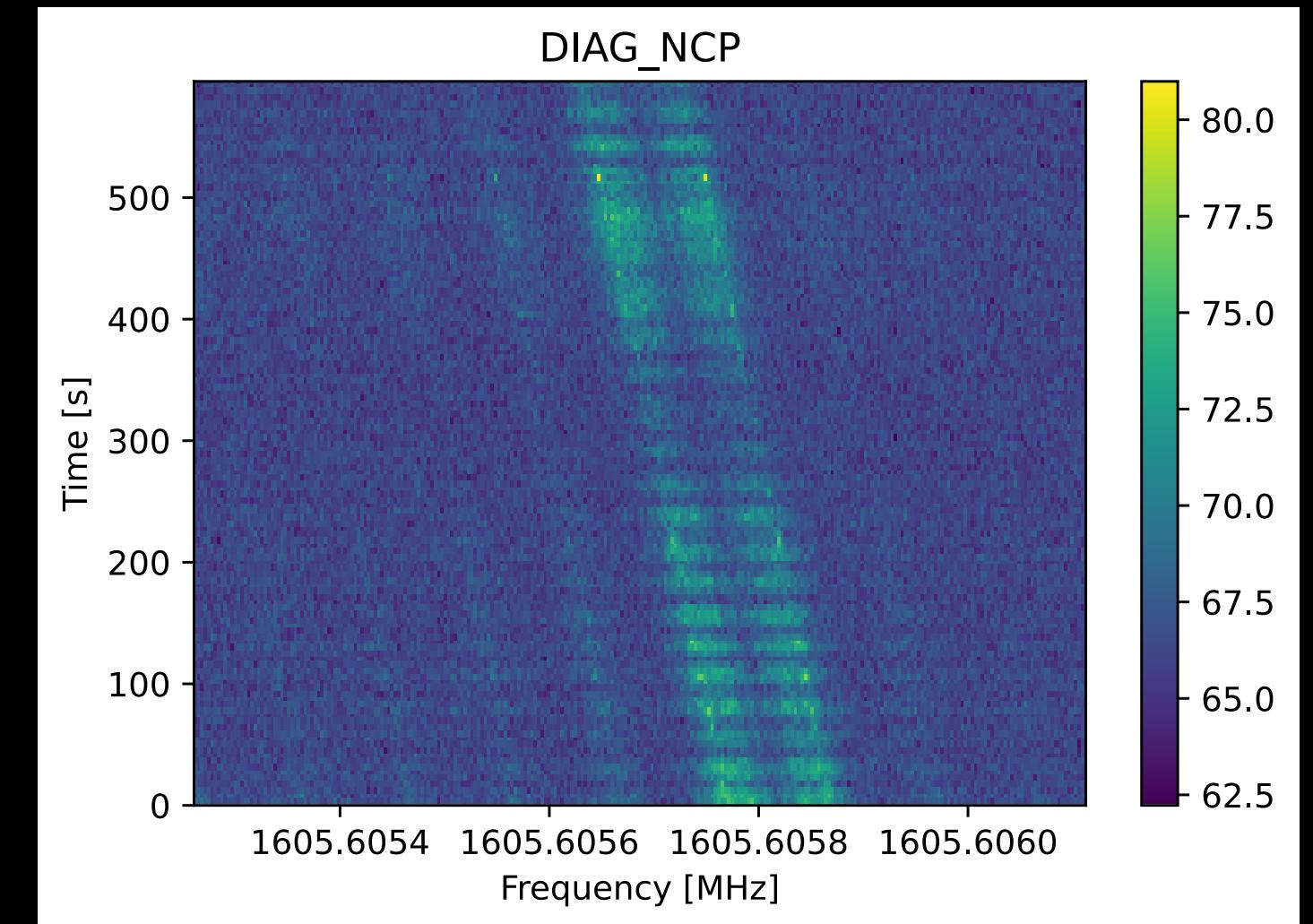
Inter-quartile range

Median



Given a signal... is it scintillated?

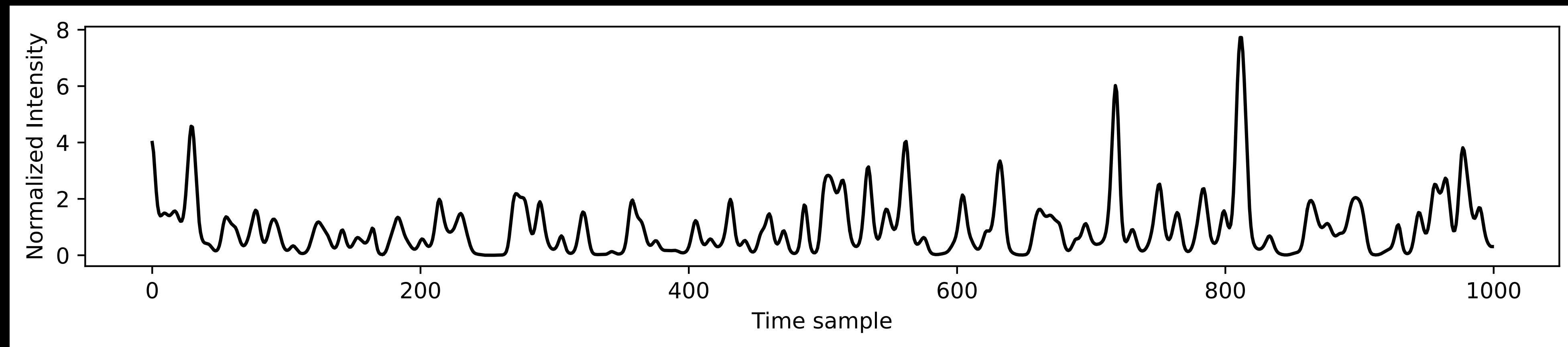
- Create bounding box around narrowband signal
- Estimate noise-subtracted intensity time series, normalized to mean 1
- Compute diagnostic statistics that pertain to asymptotic behavior
 - E.g. standard deviation, Kolmogorov-Smirnov statistic, fit to autocorrelation function



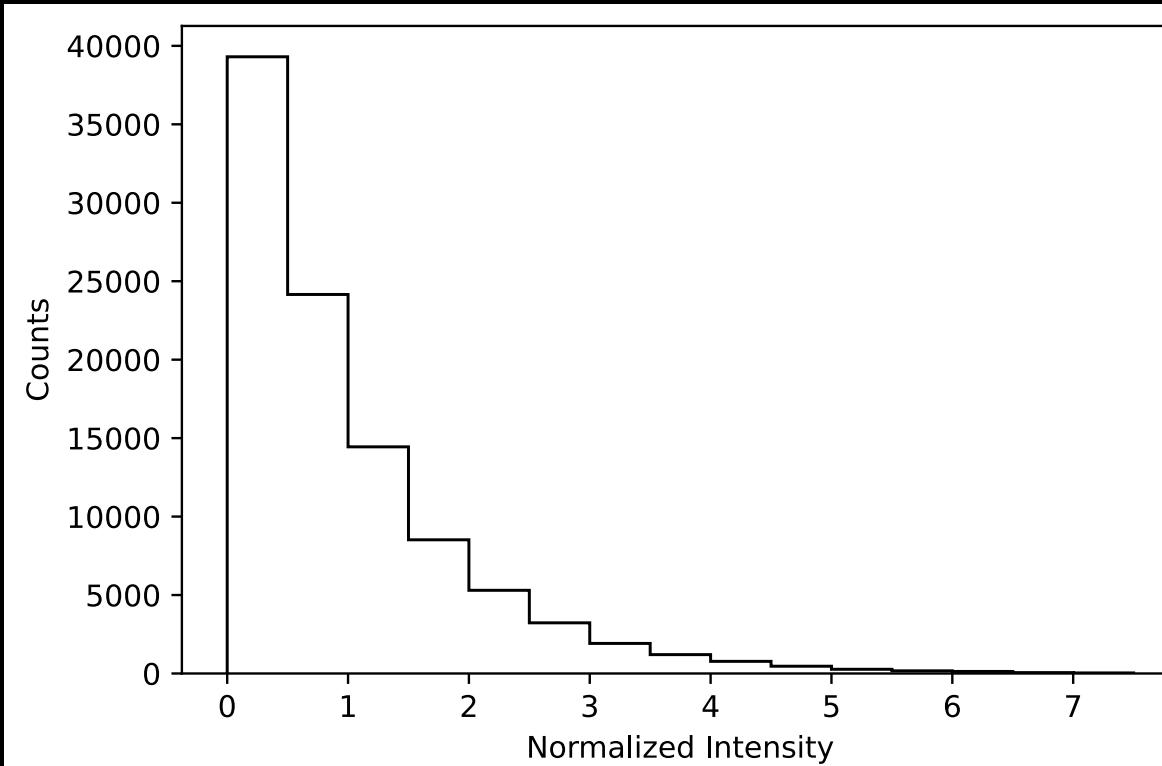
Quick way to produce synthetic data with asymptotic statistics

- (Cario & Nelson 1996) The ARTA random process matches:

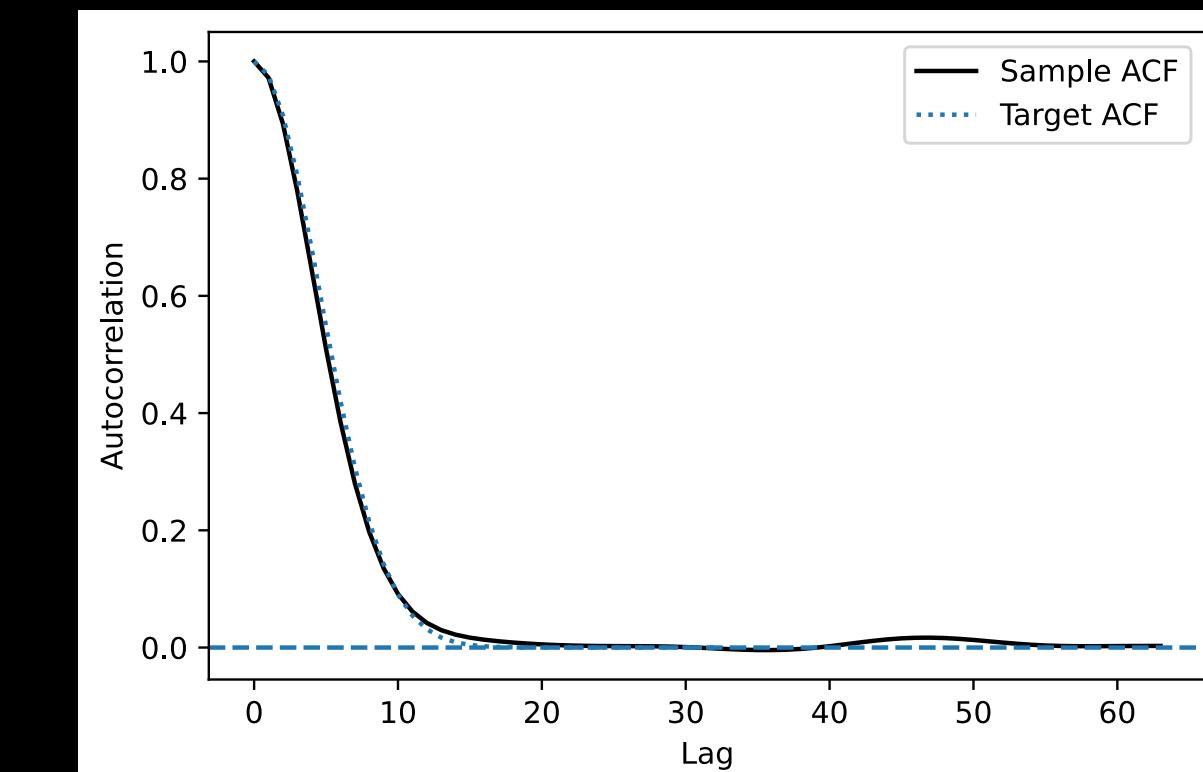
- Target intensity distribution
- Target autocorrelation structure (with custom asymptotic precision)



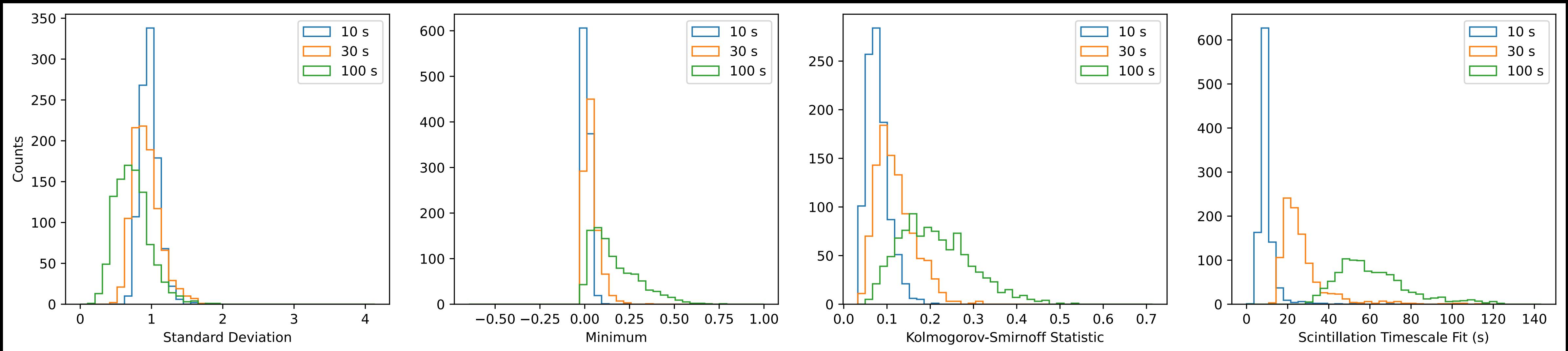
Intensity histogram



Autocorrelation



Statistics using low number of synthetic samples



Std. Dev.

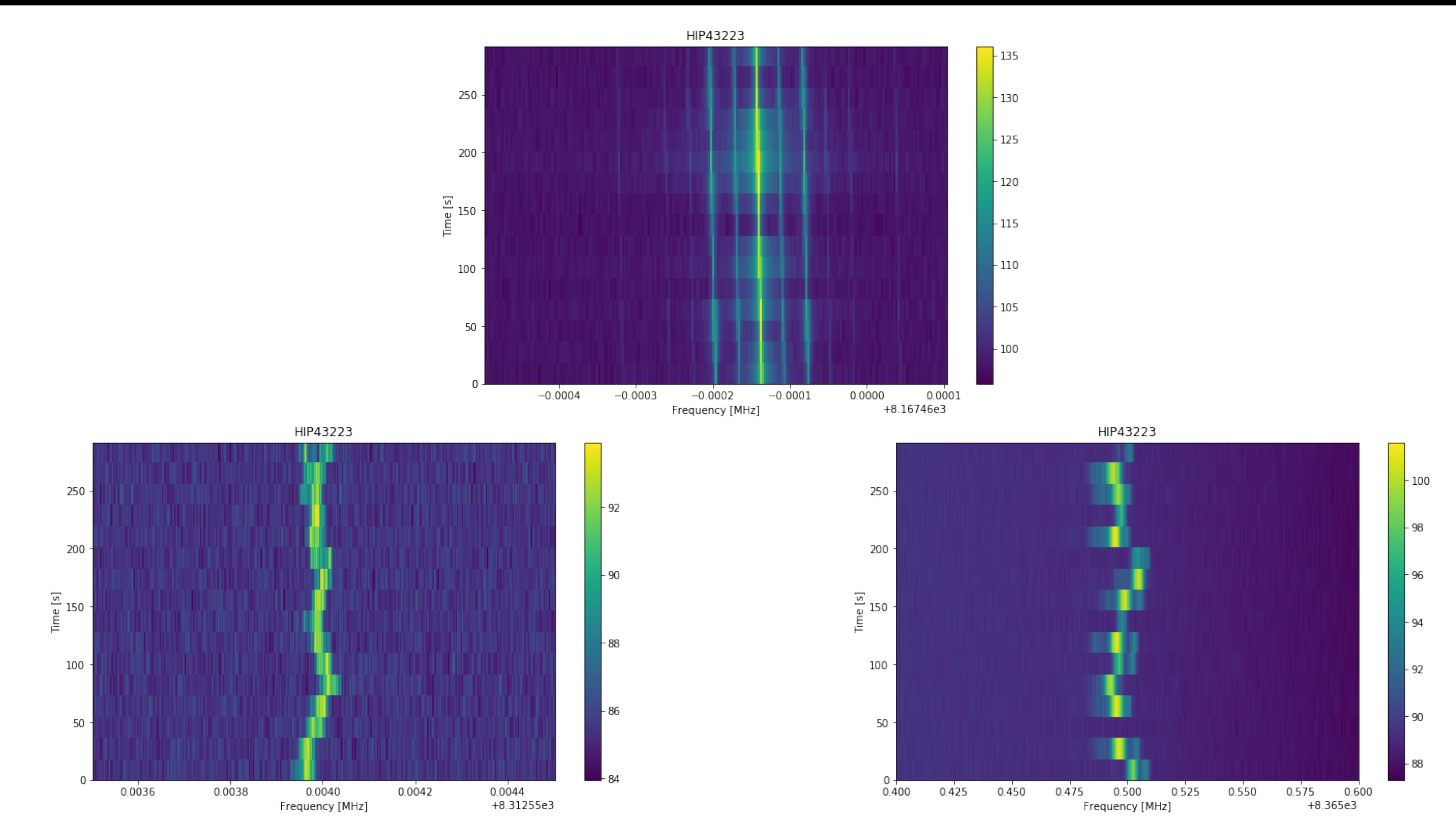
Minimum

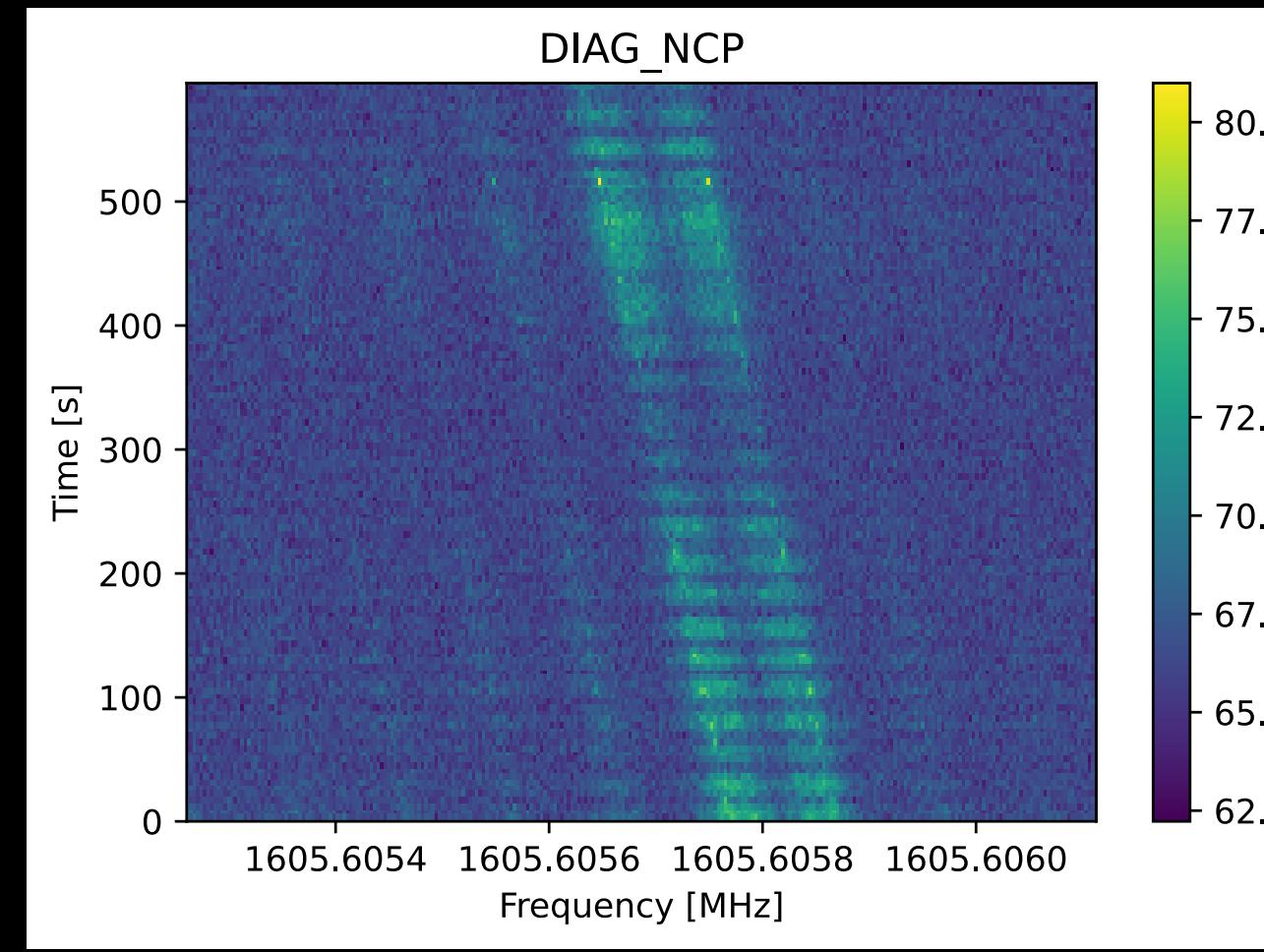
KS Statistic

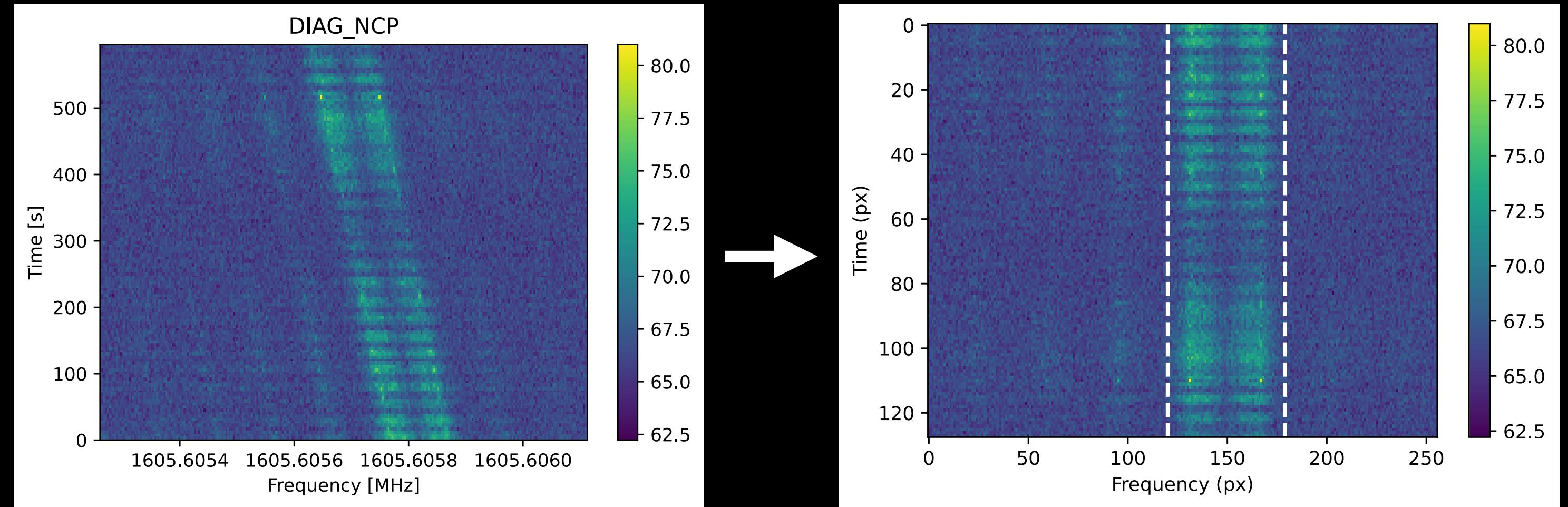
Timescale Fit

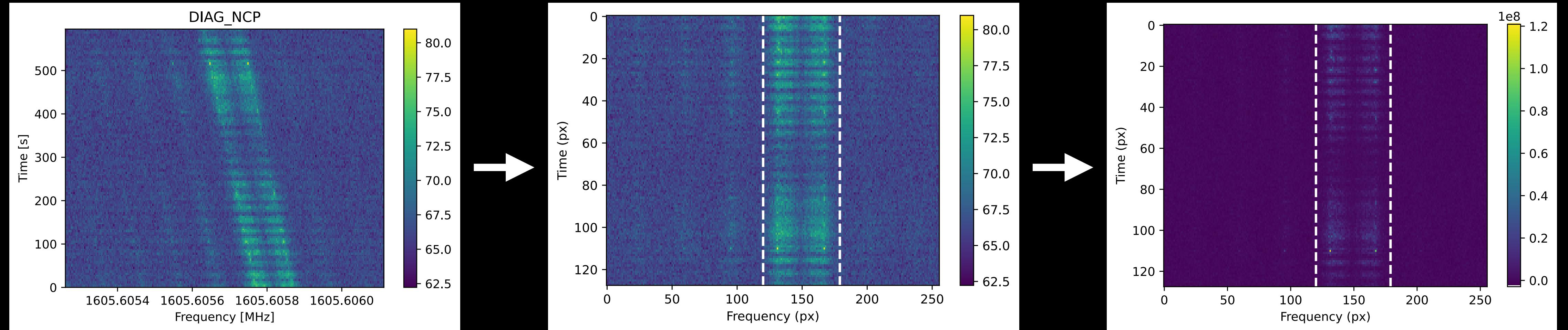
10 min “observation”, 4.65 s resolution

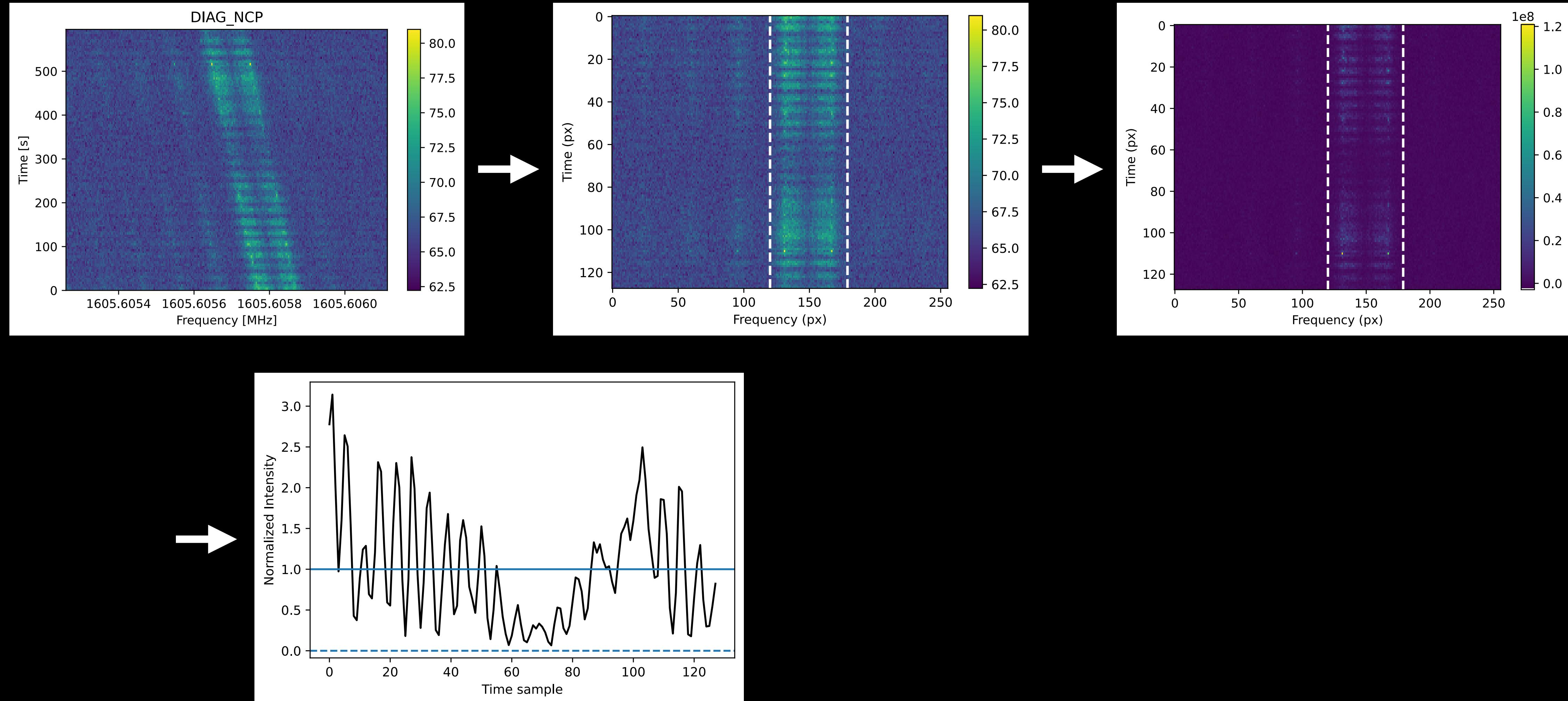
But what does the RFI environment look like?

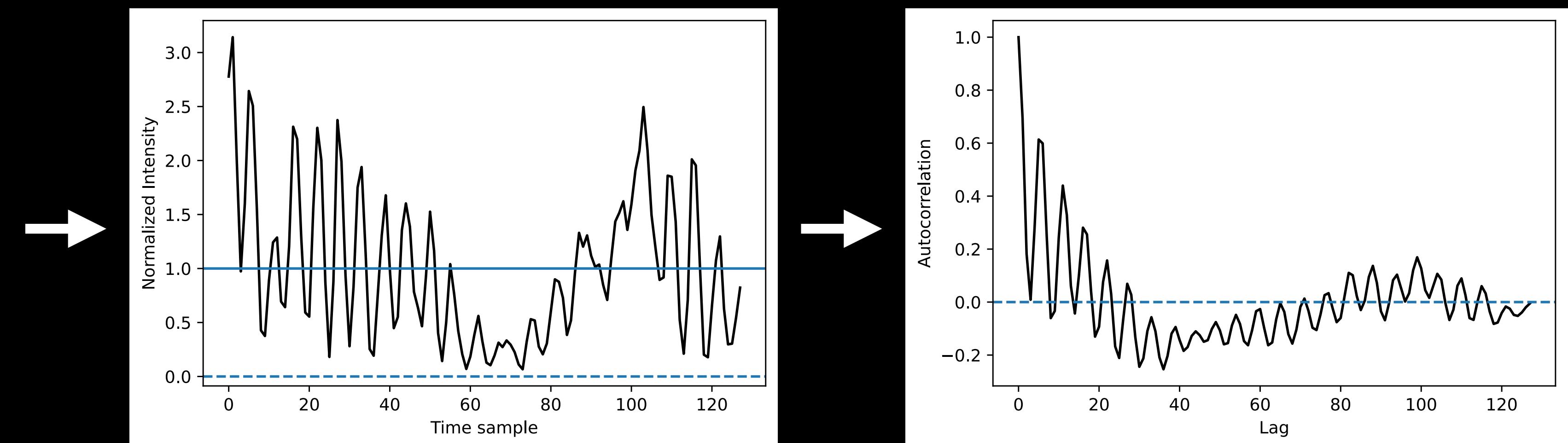
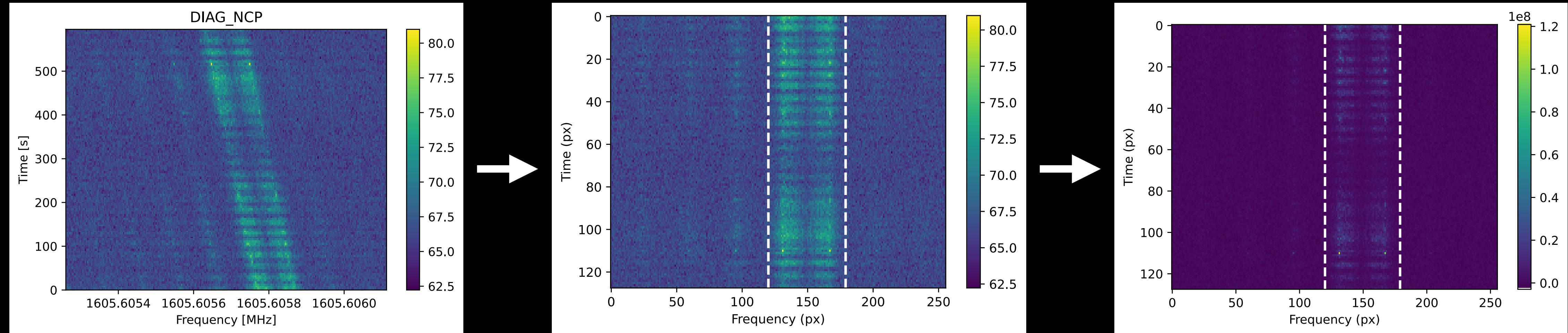








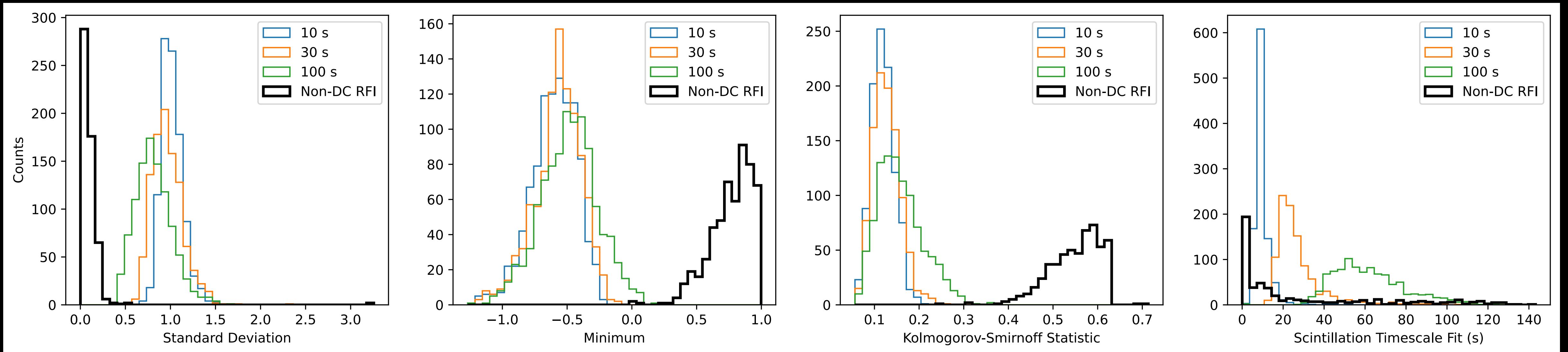




Diagnostic statistics

C band

S/N = 25



Std. Dev.

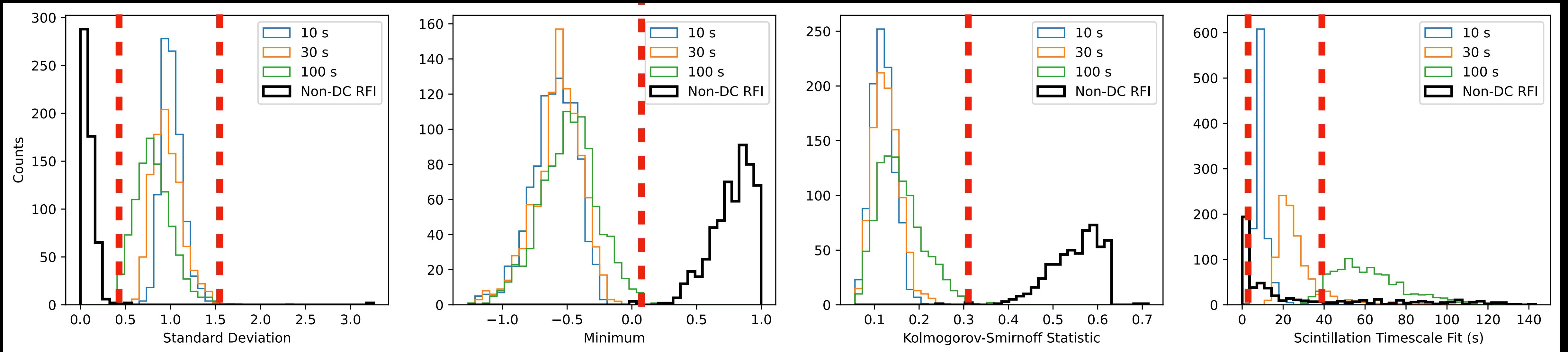
Minimum

KS Statistic

Timescale Fit

C band

S/N = 25



Std. Dev.

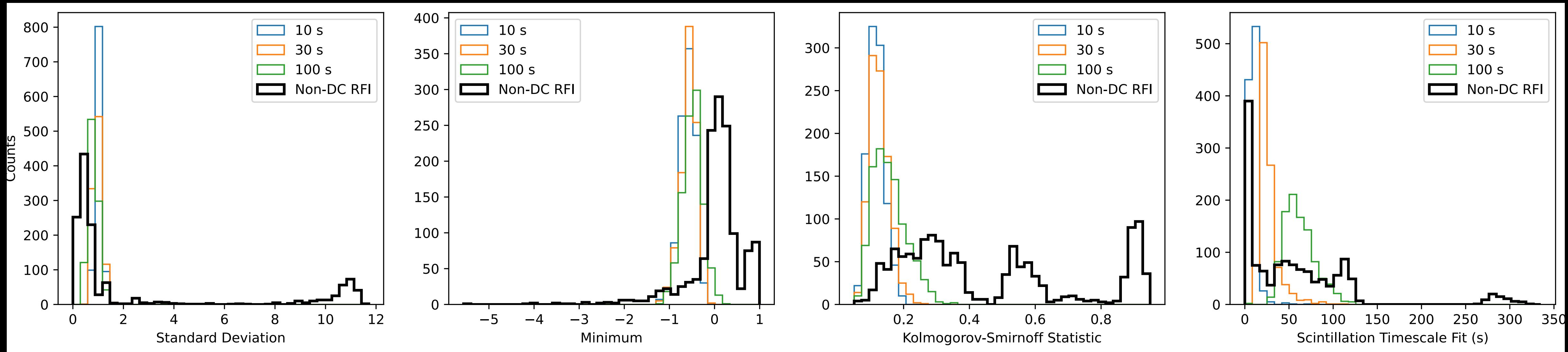
Minimum

KS Statistic

Timescale Fit

L band

S/N = 25



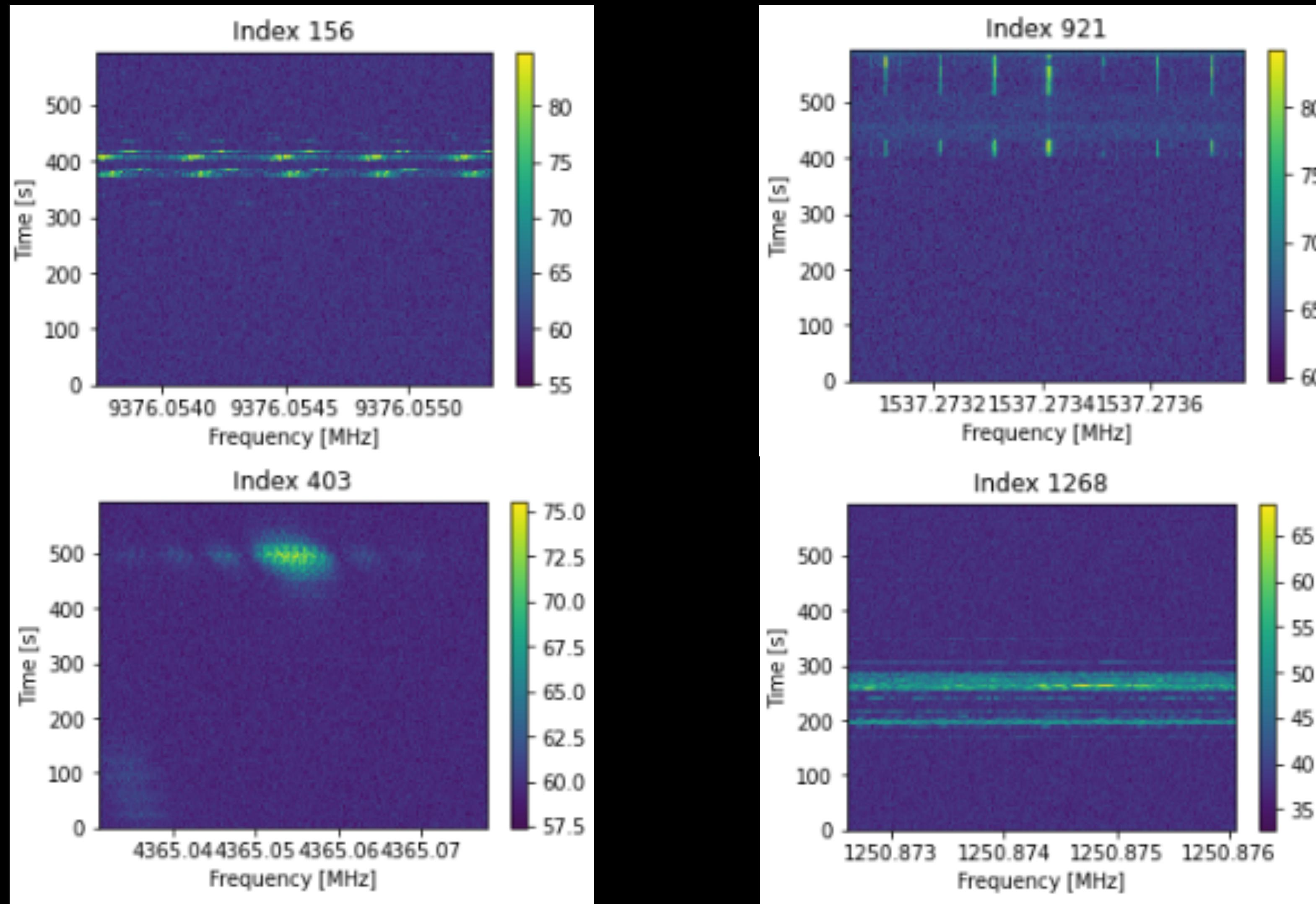
Std. Dev.

Minimum

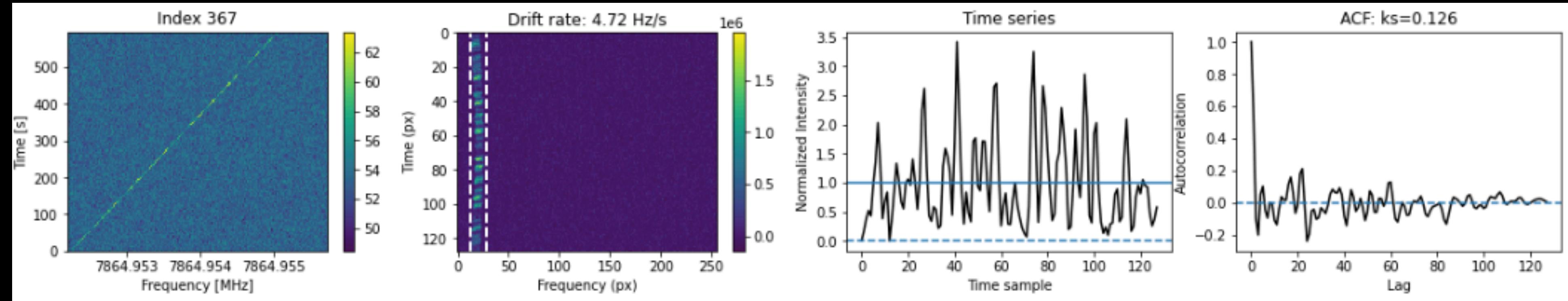
KS Statistic

Timescale Fit

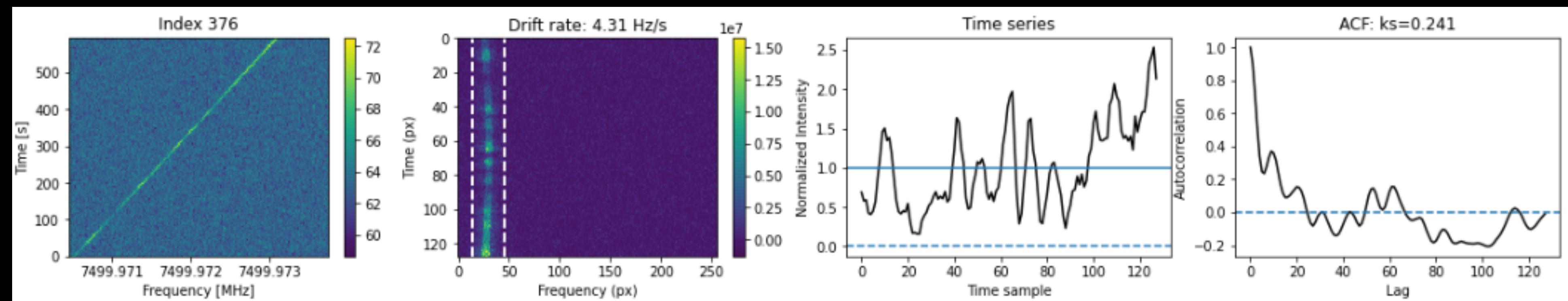
High standard deviation (RMS) signals are pulsed - or broadband



What signals pass the threshold?



Timescale fit ~ 2 s

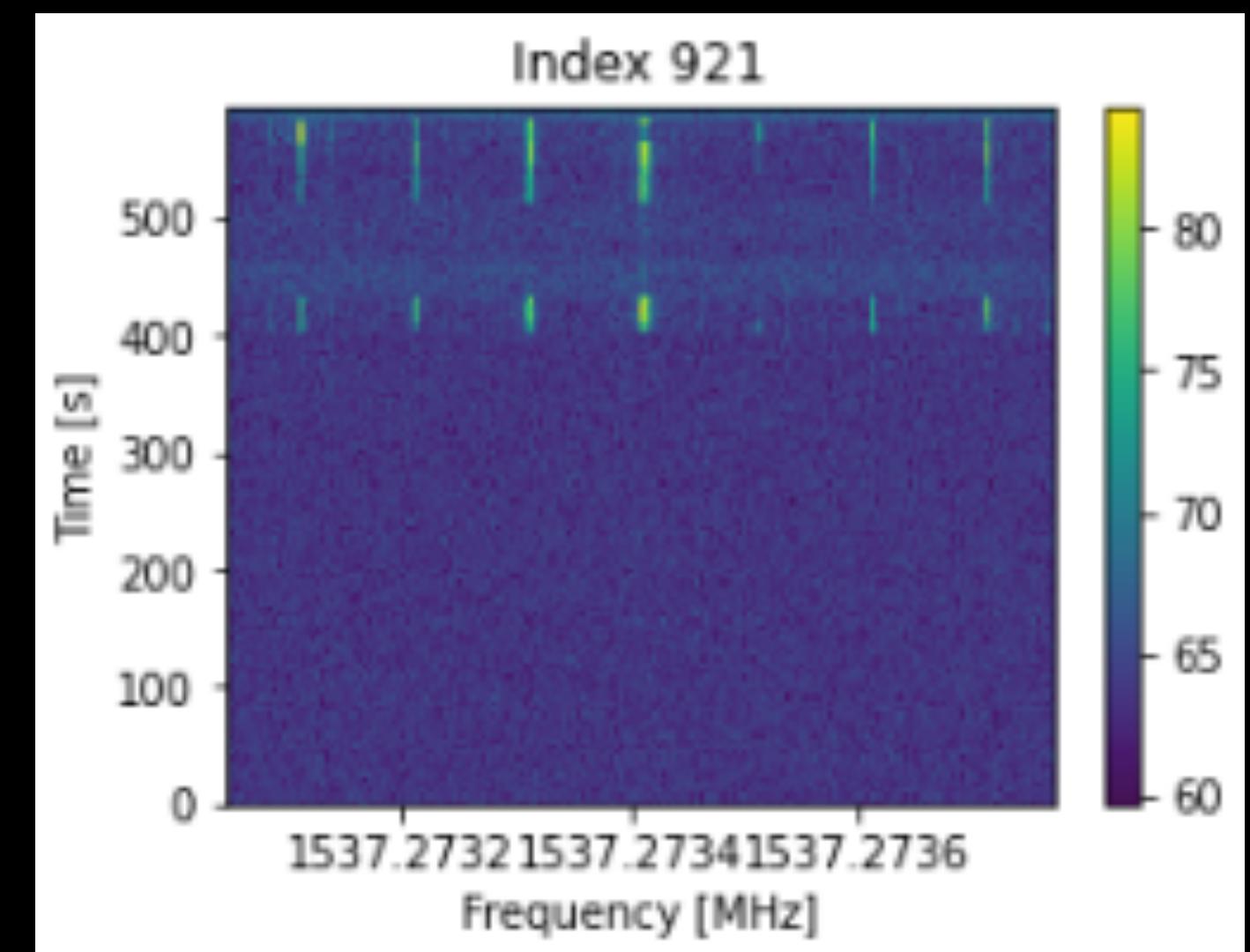
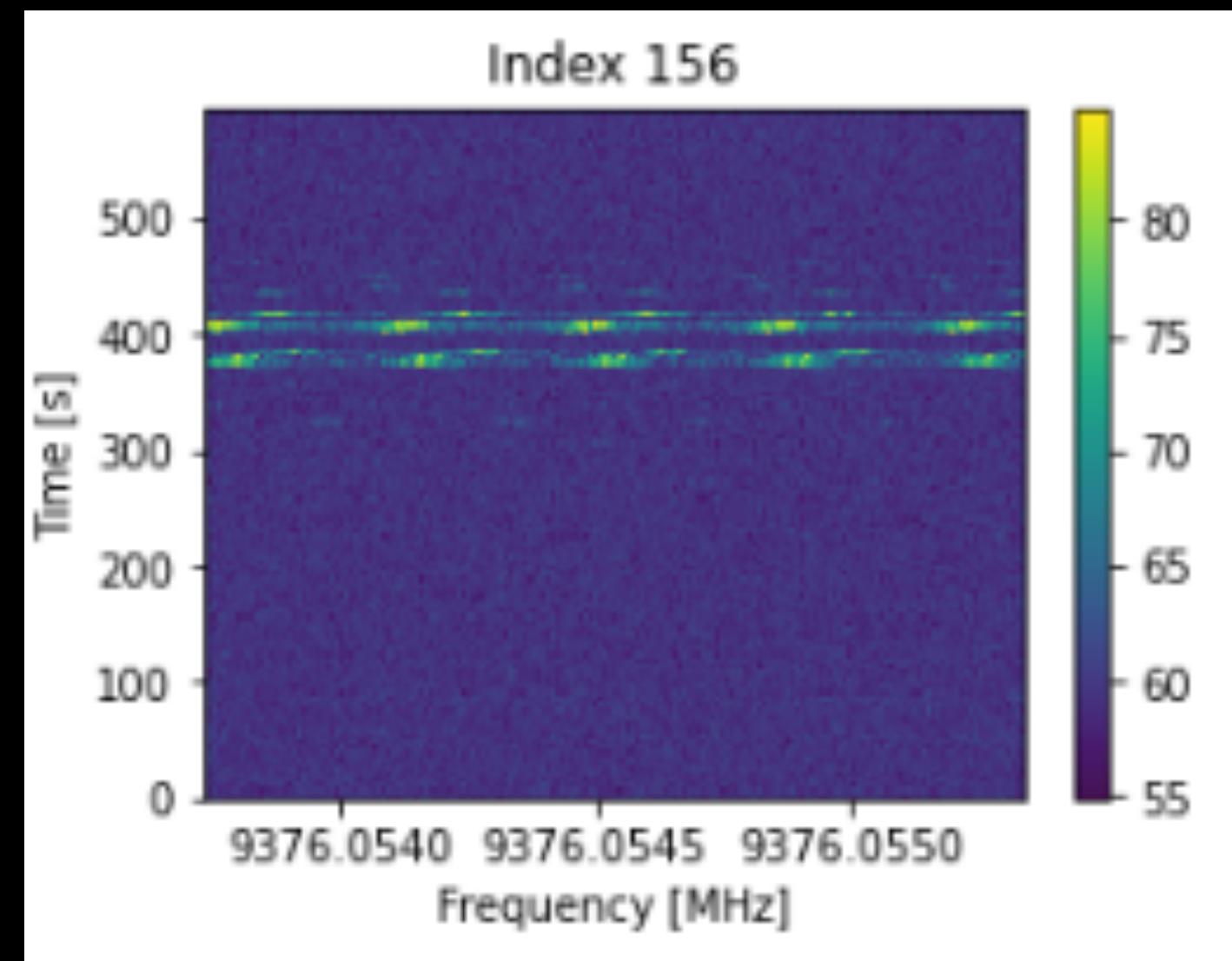


Timescale fit ~ 60 s

- 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!

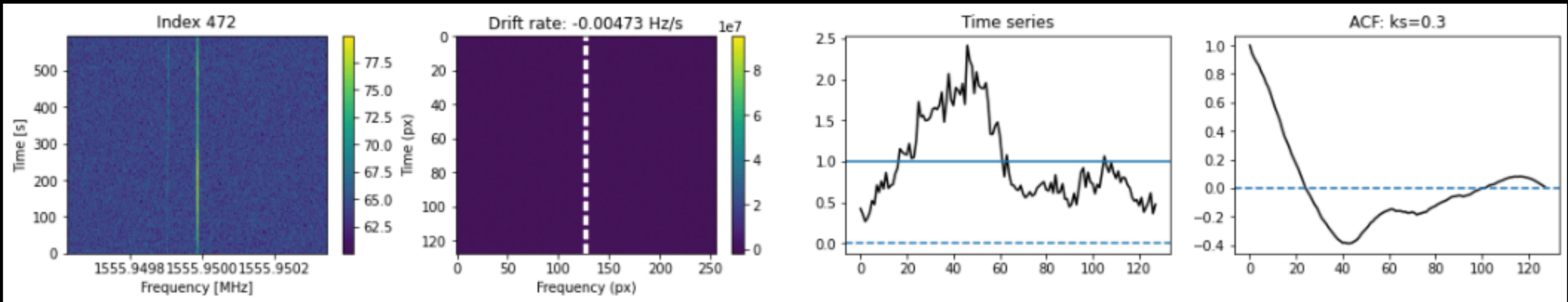
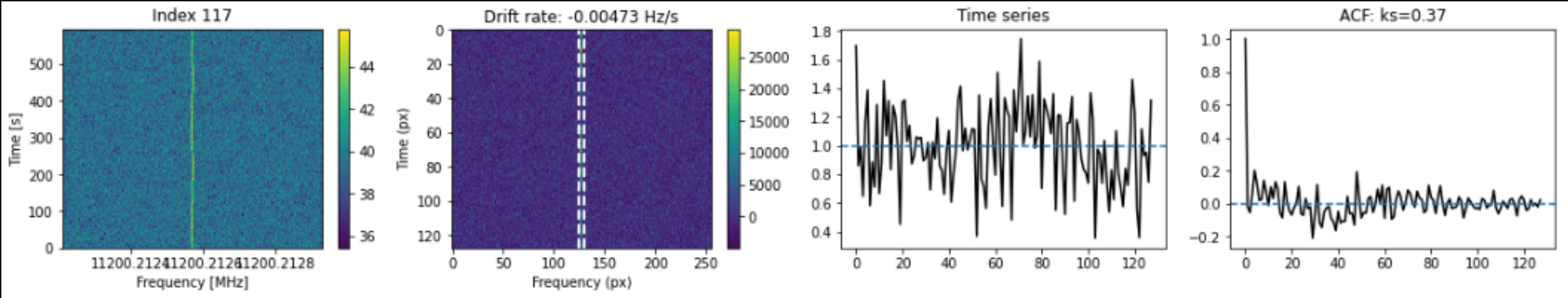


Summary

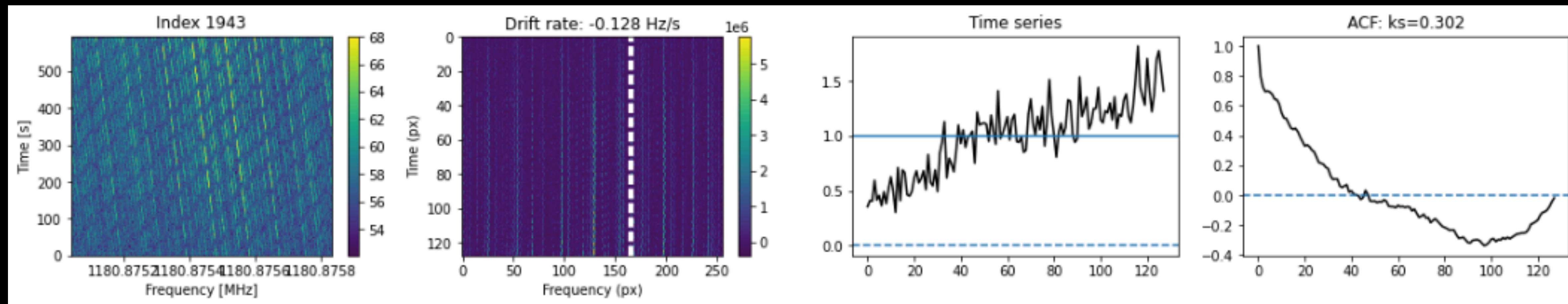
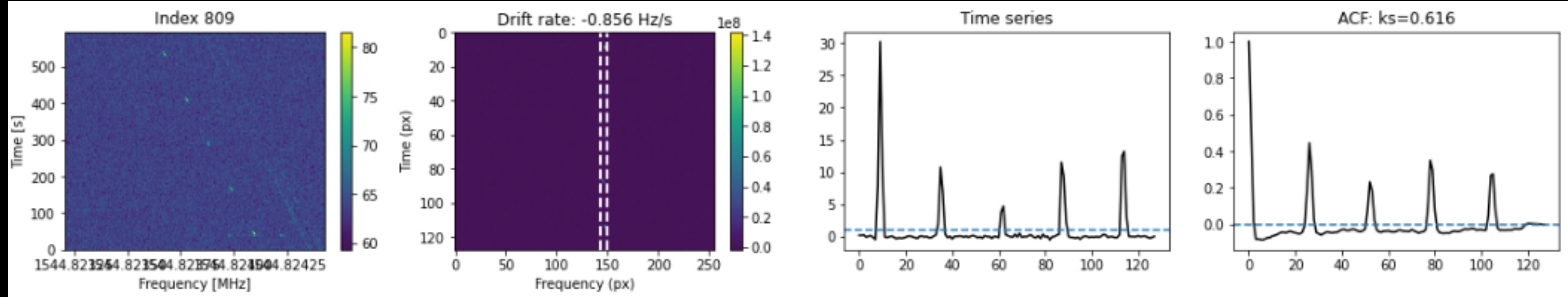
- Developed a framework for scintillation analysis, with accompanying code
- Because of RFI environment, higher frequencies are more amenable
- Looking forward: dedicated survey with custom resolution to search near the Galactic Center
- Better extraction / classification methods may lead to improvements

Extra Slides

Some examples



Some more examples



Examples of diagnostic statistics

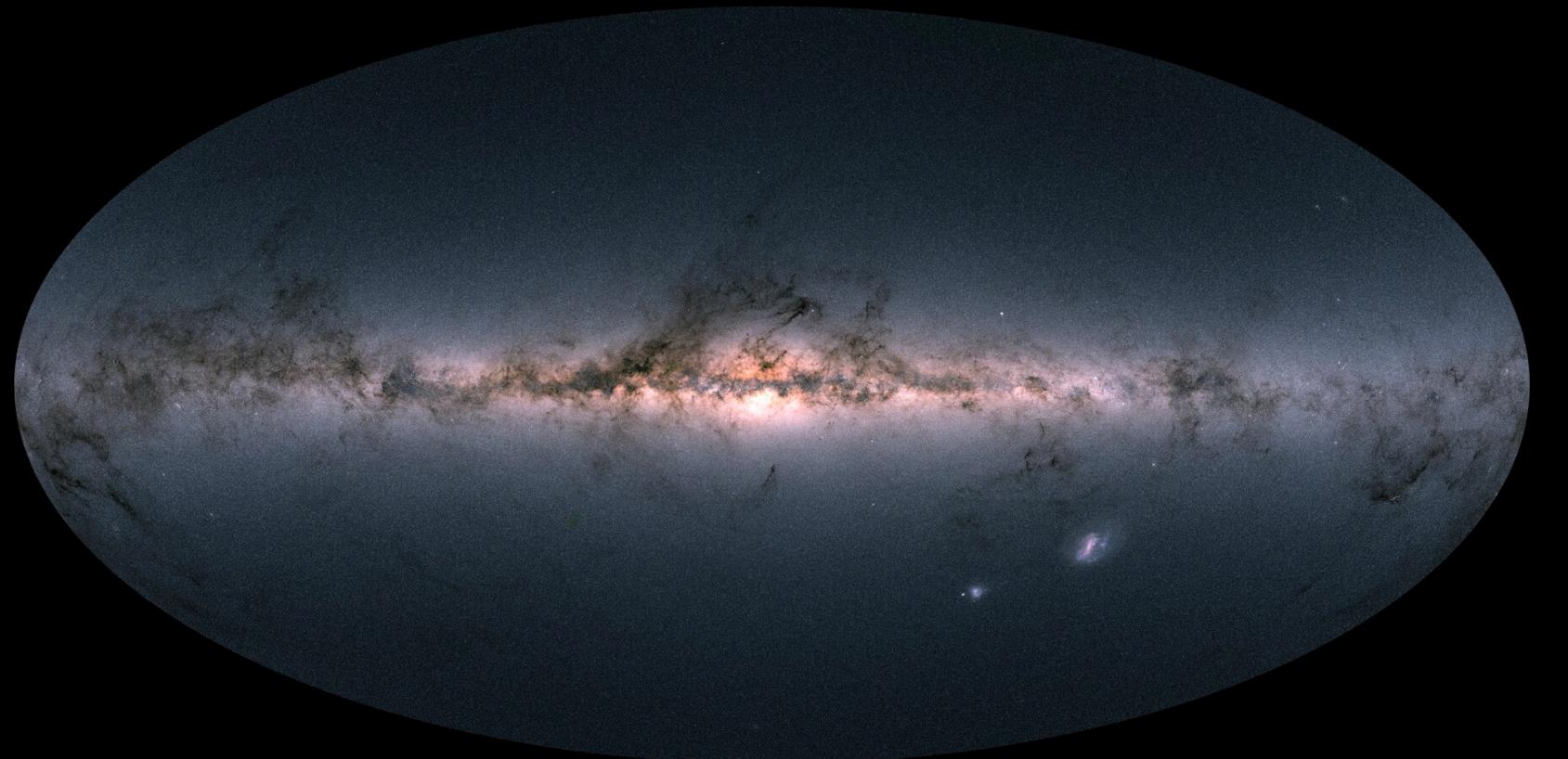
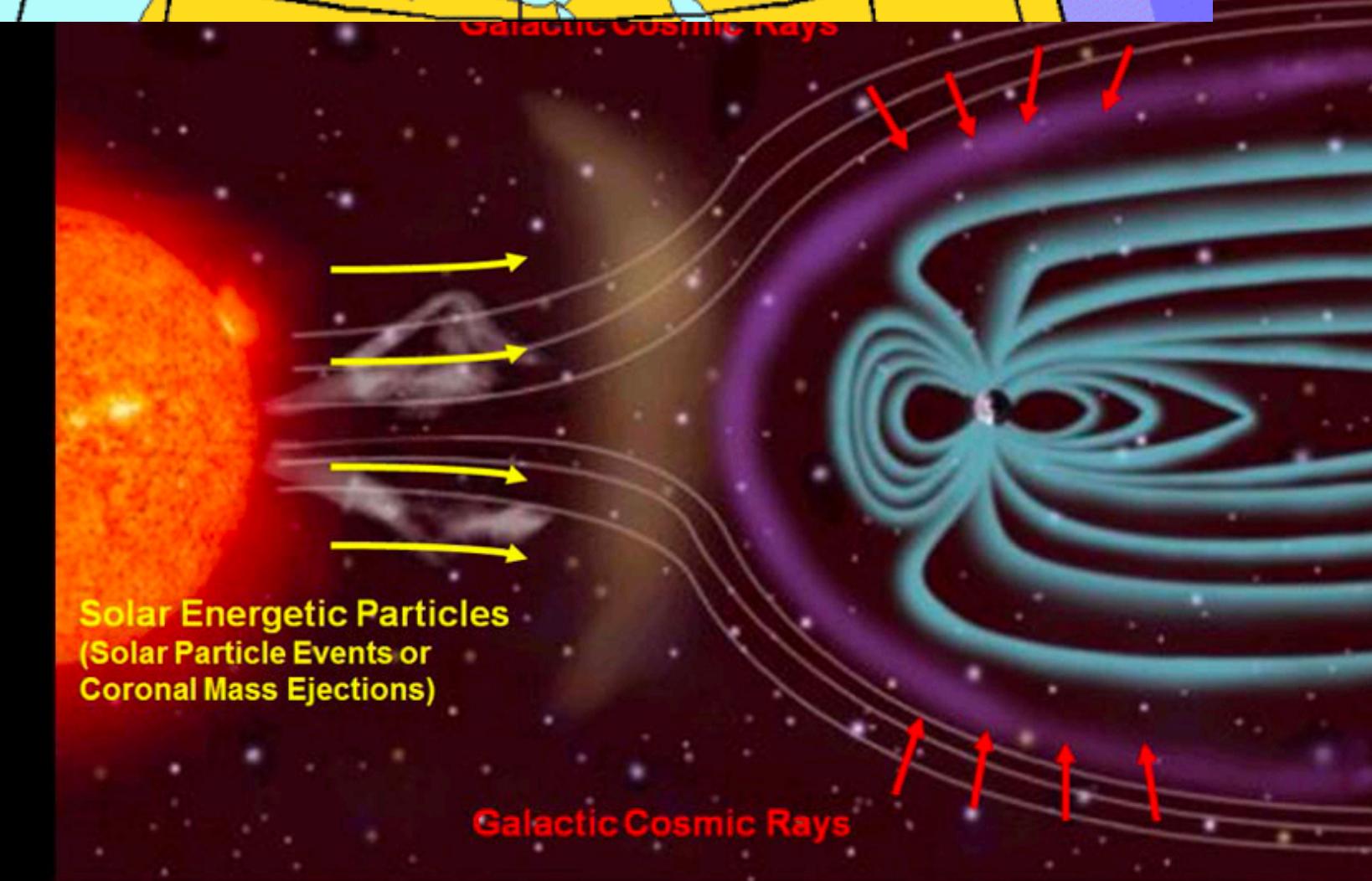
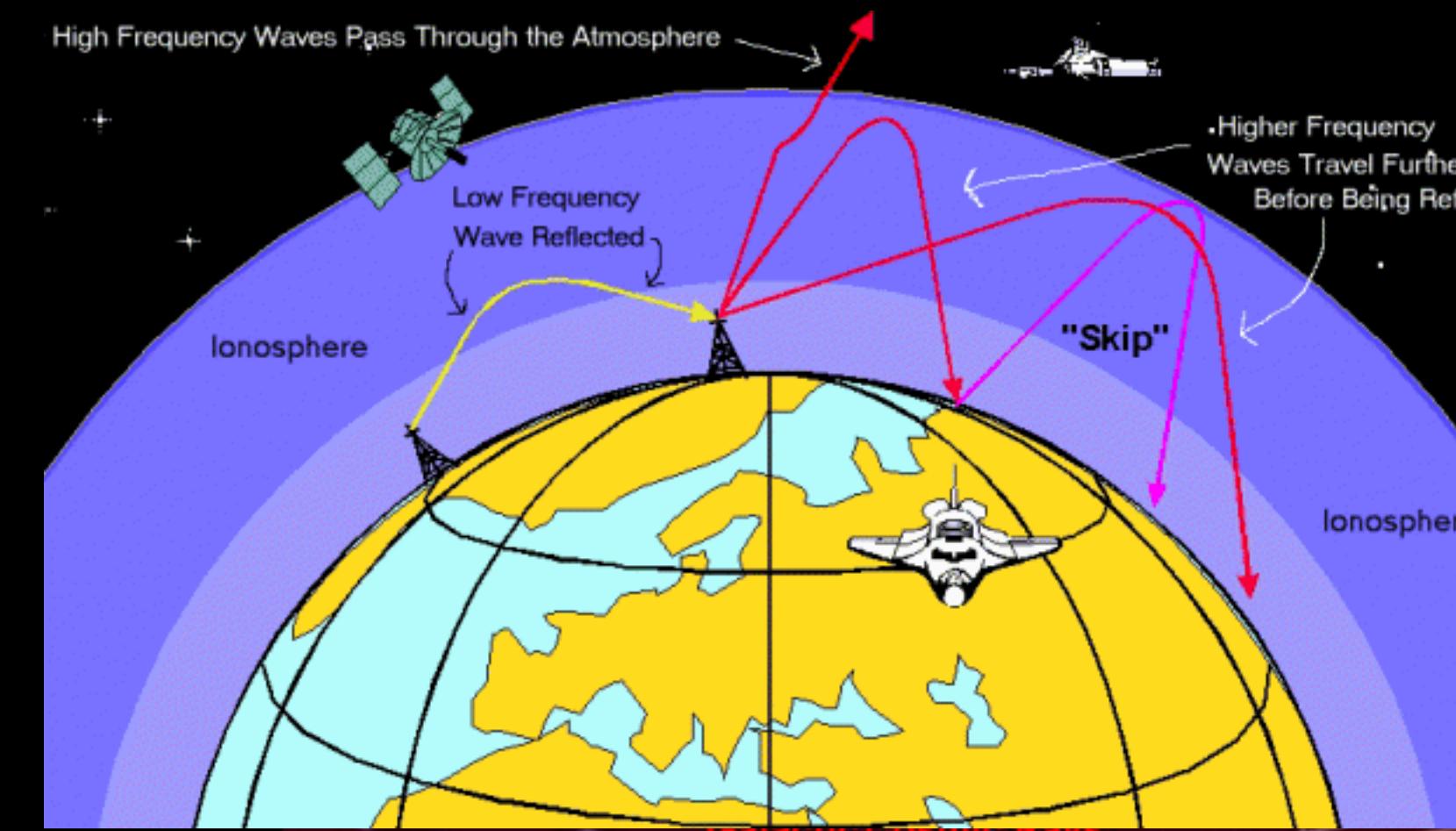
Statistic	Asymptotic Value (with no noise)	Target Distribution
Standard Deviation (RMS)	1	Intensity, exponential
Minimum	0	Intensity, exponential
Kolmogorov-Smirnoff statistic	0	Intensity, exponential
Autocorrelation lag	Variable	Autocorrelation, Gaussian
Least squares fit to autocorrelation	Variable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

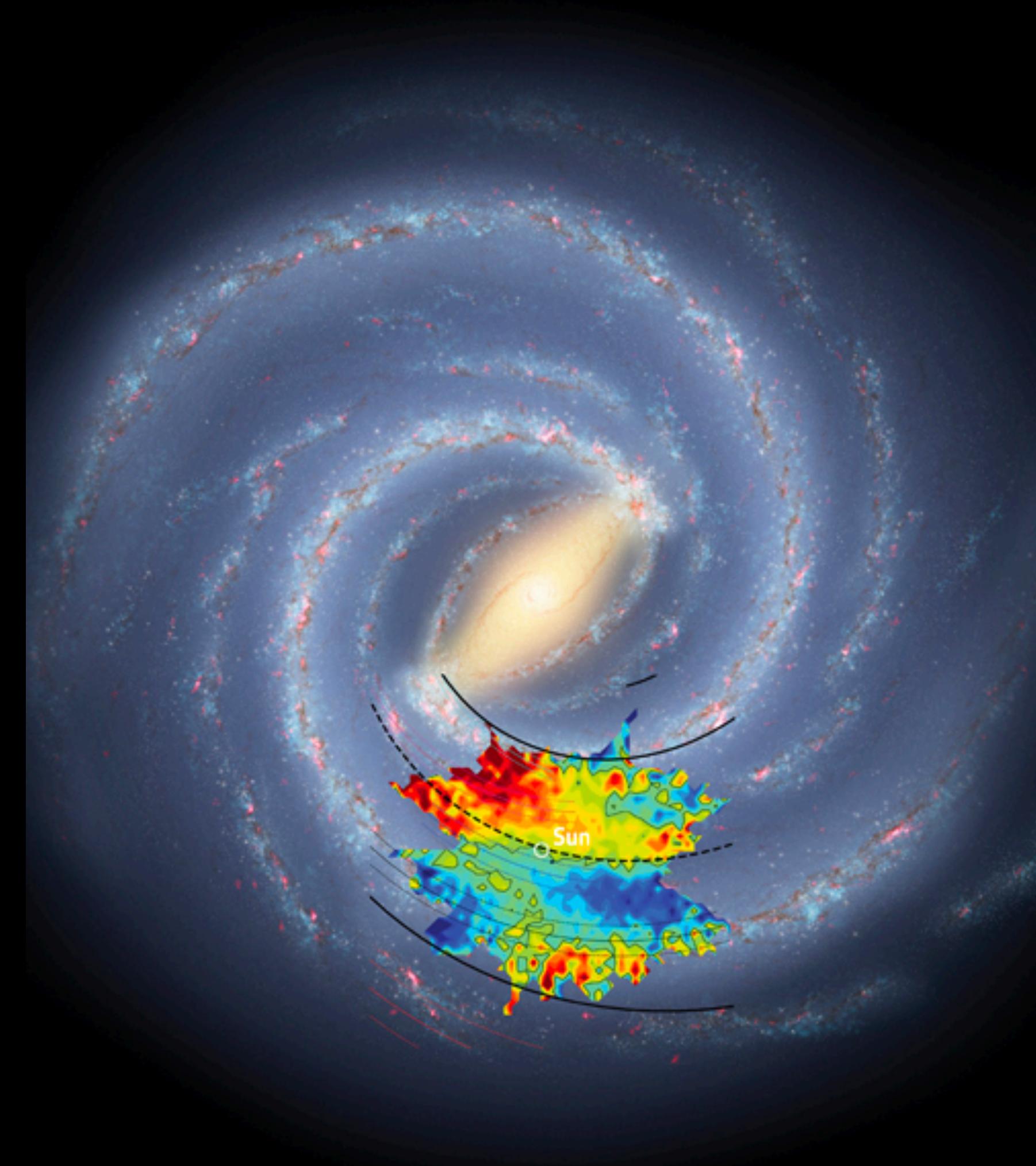
Regions of ionized plasma

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



Next steps: a Galactic Center / Galactic Plane survey

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



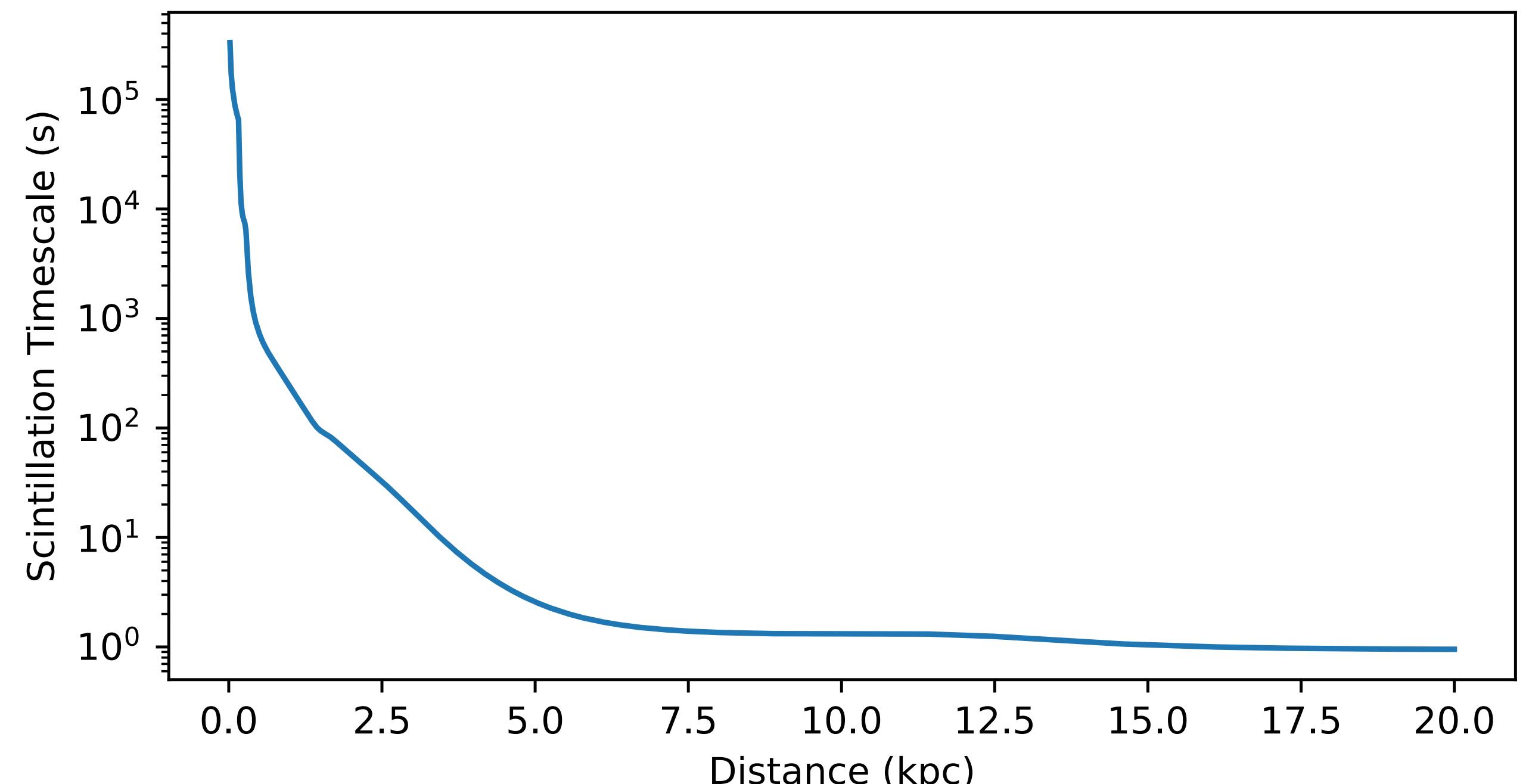
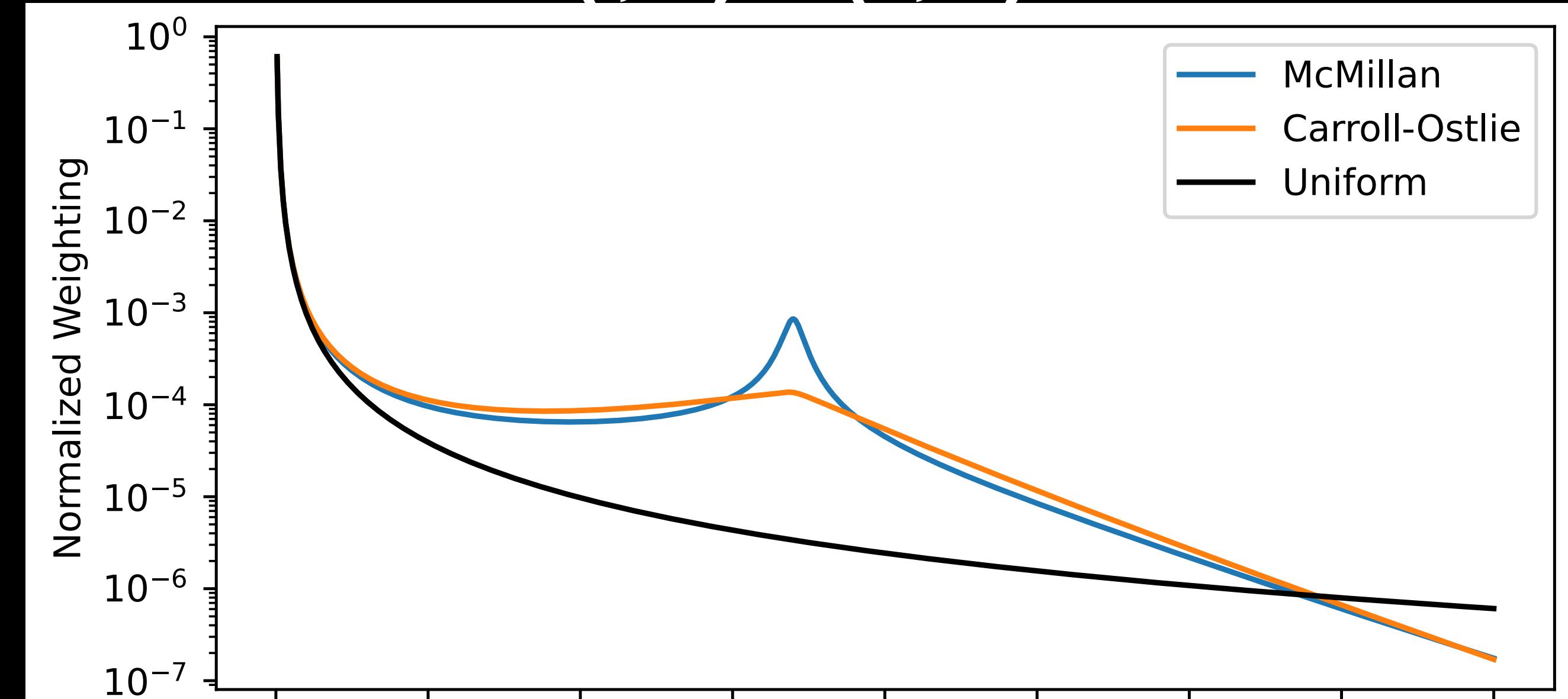
Gaia

$(l, b) = (1, 0)$

Density-based sampling

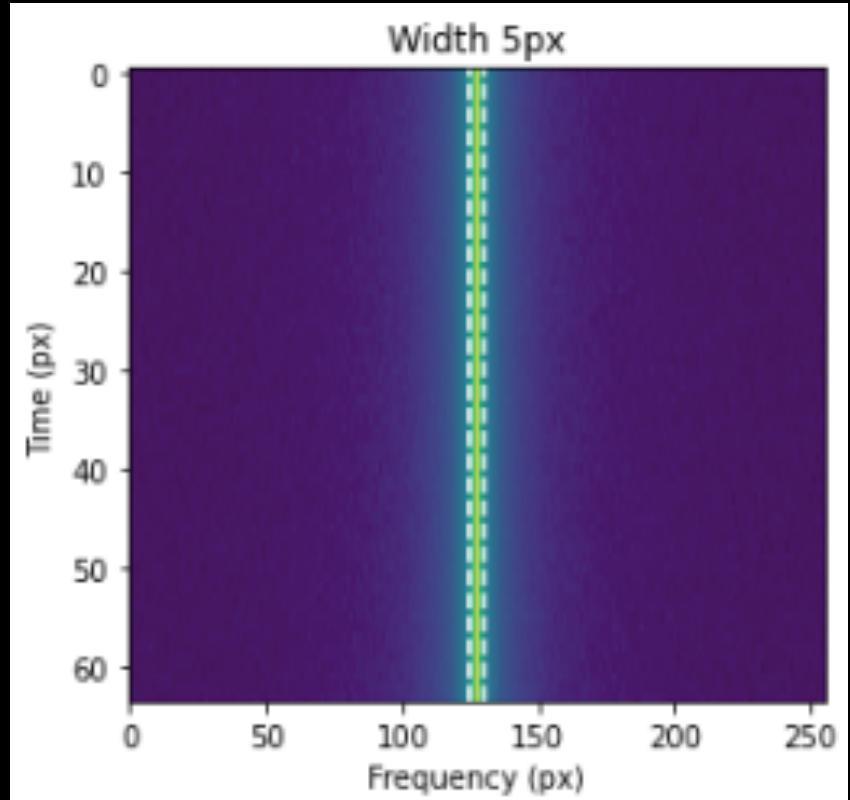
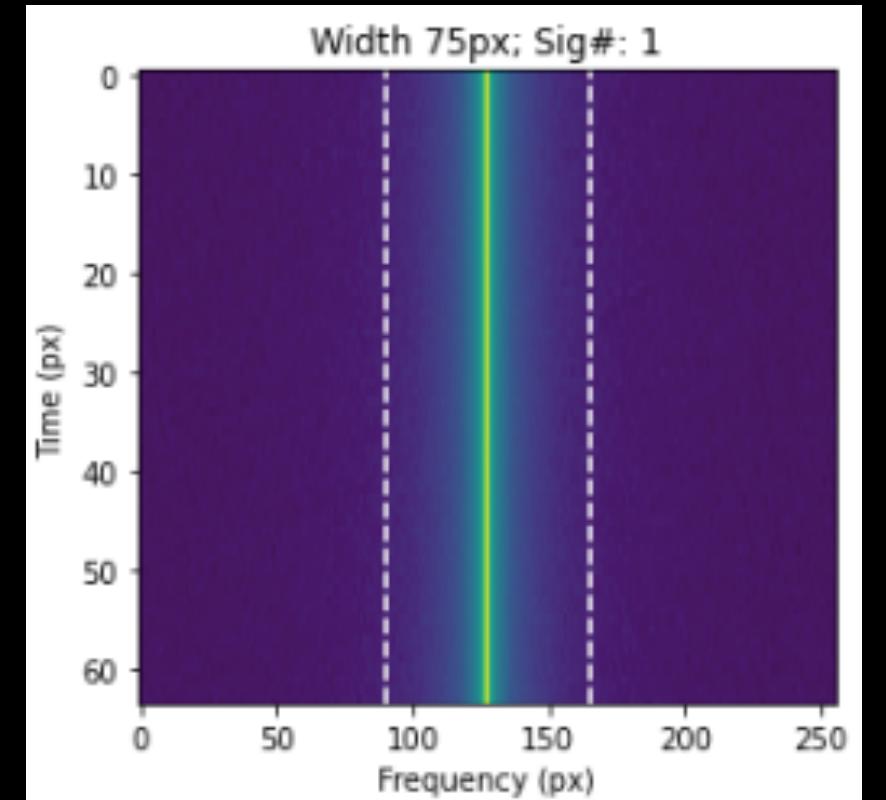
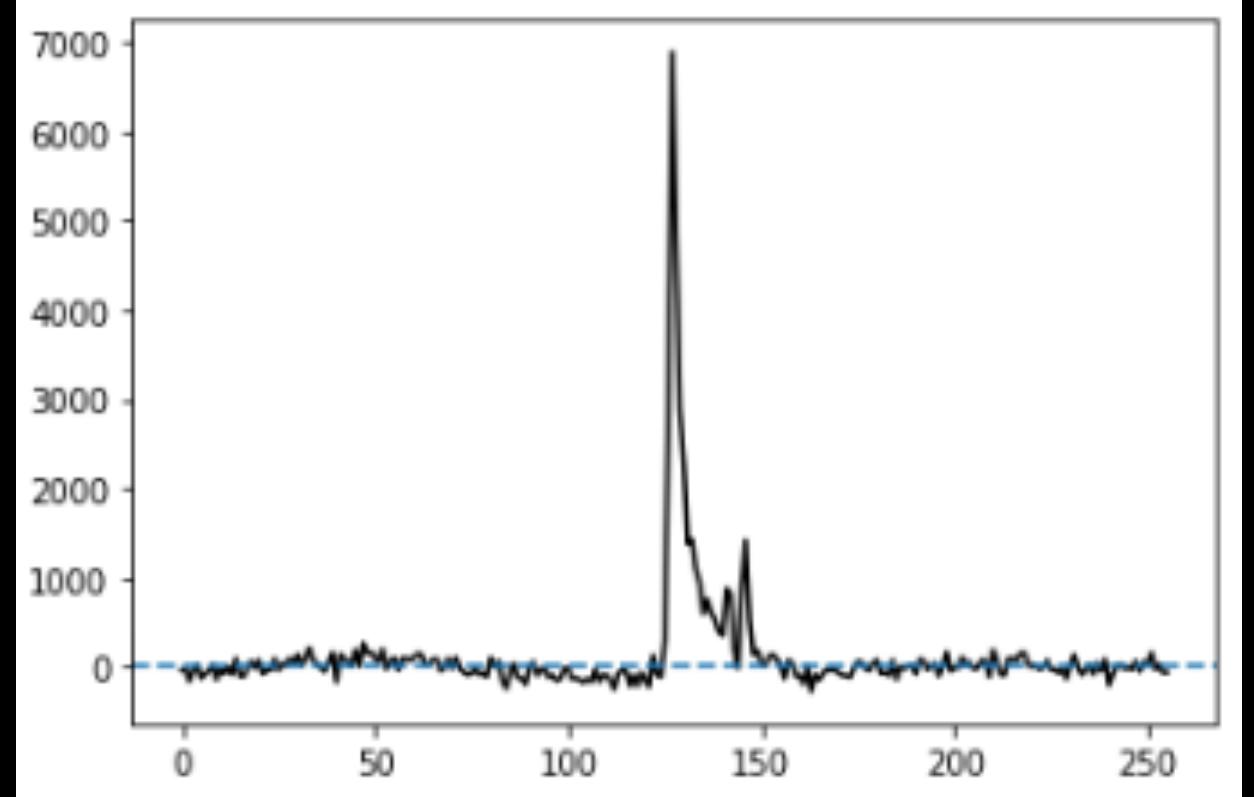
Modulating by the inverse square-law for detectability:

Depends on the assumptions made about transmission power and resources.



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

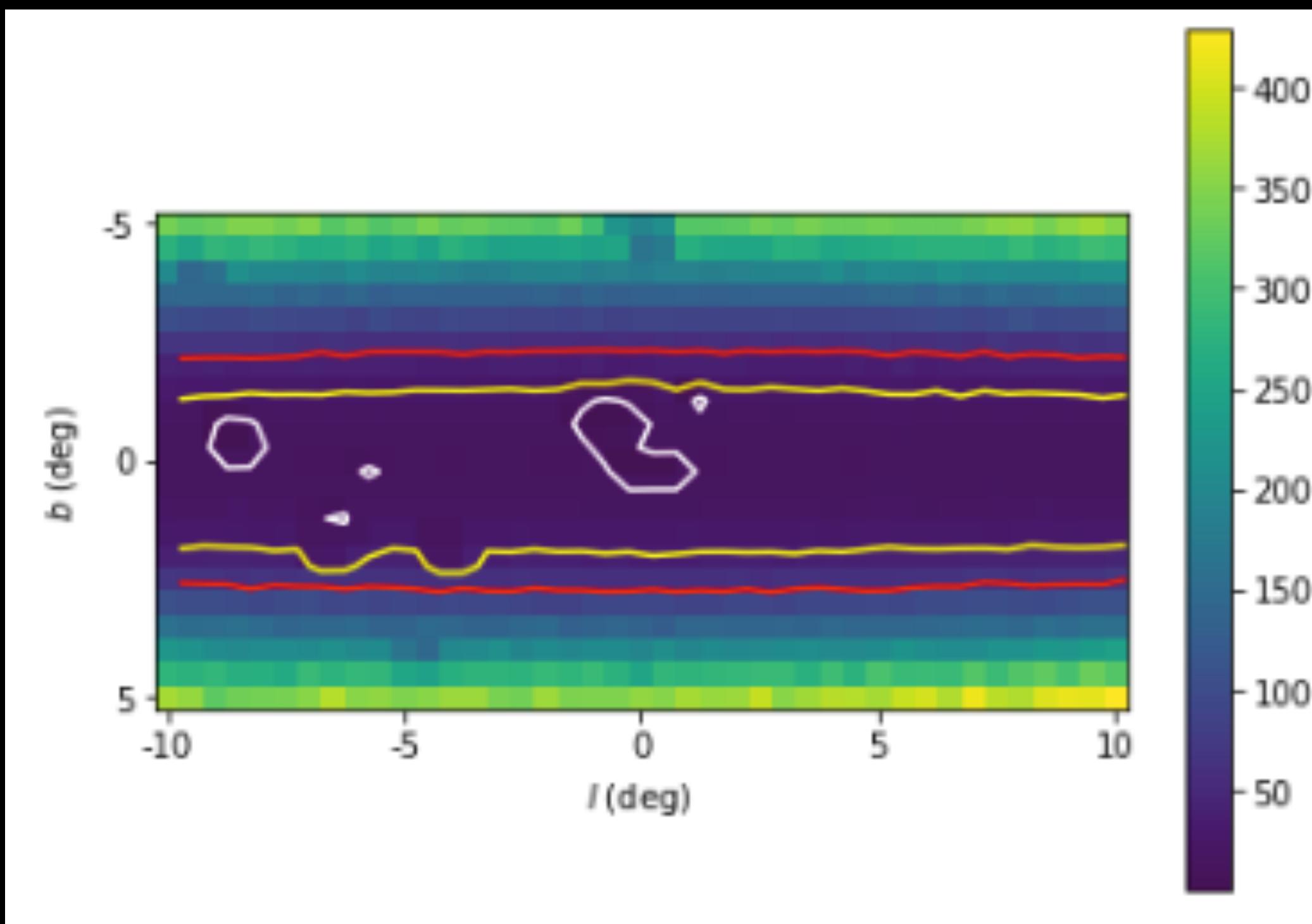


Polynomial fit

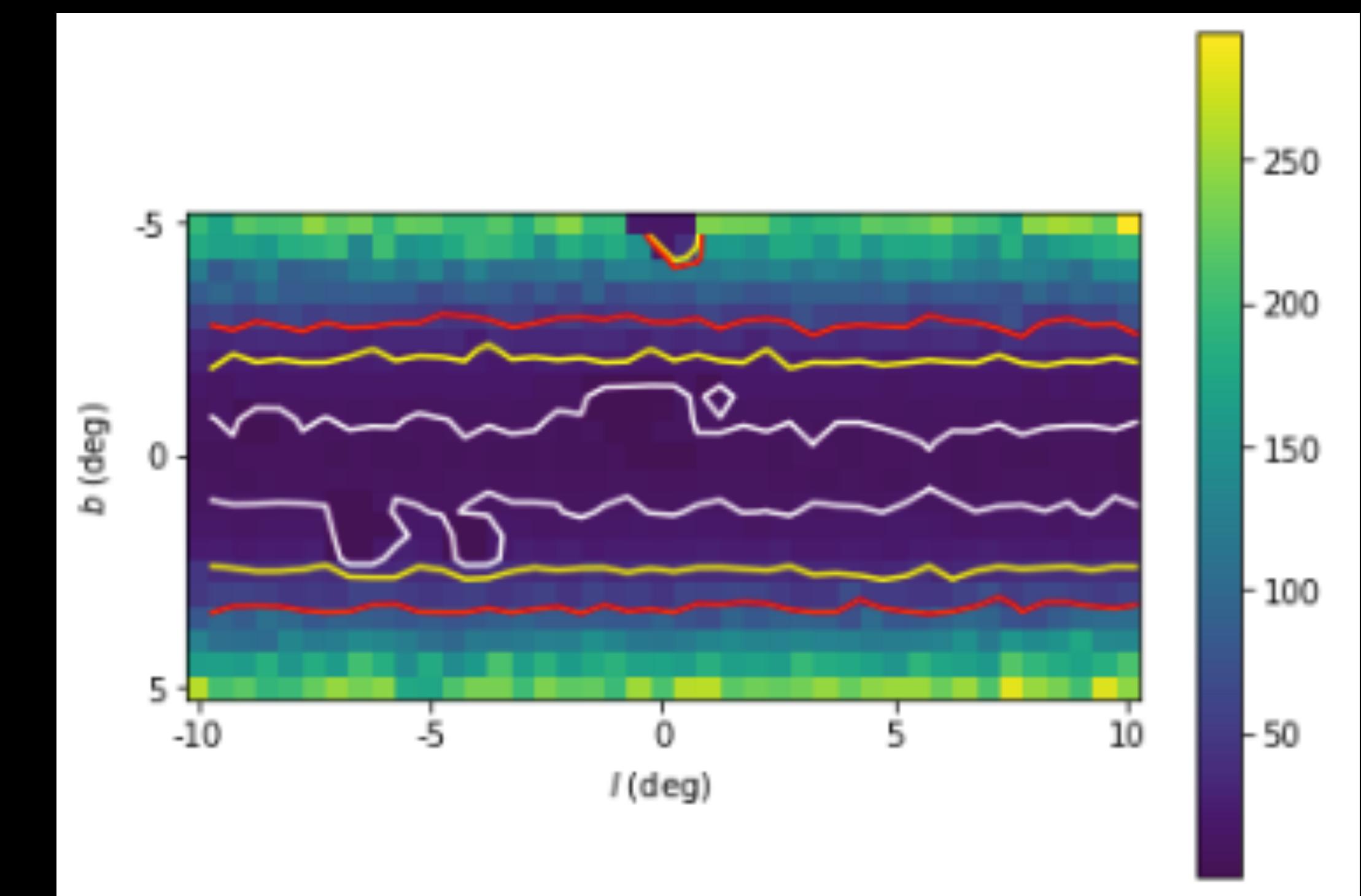
Threshold fit

Scintillation maps around the GC at C-band

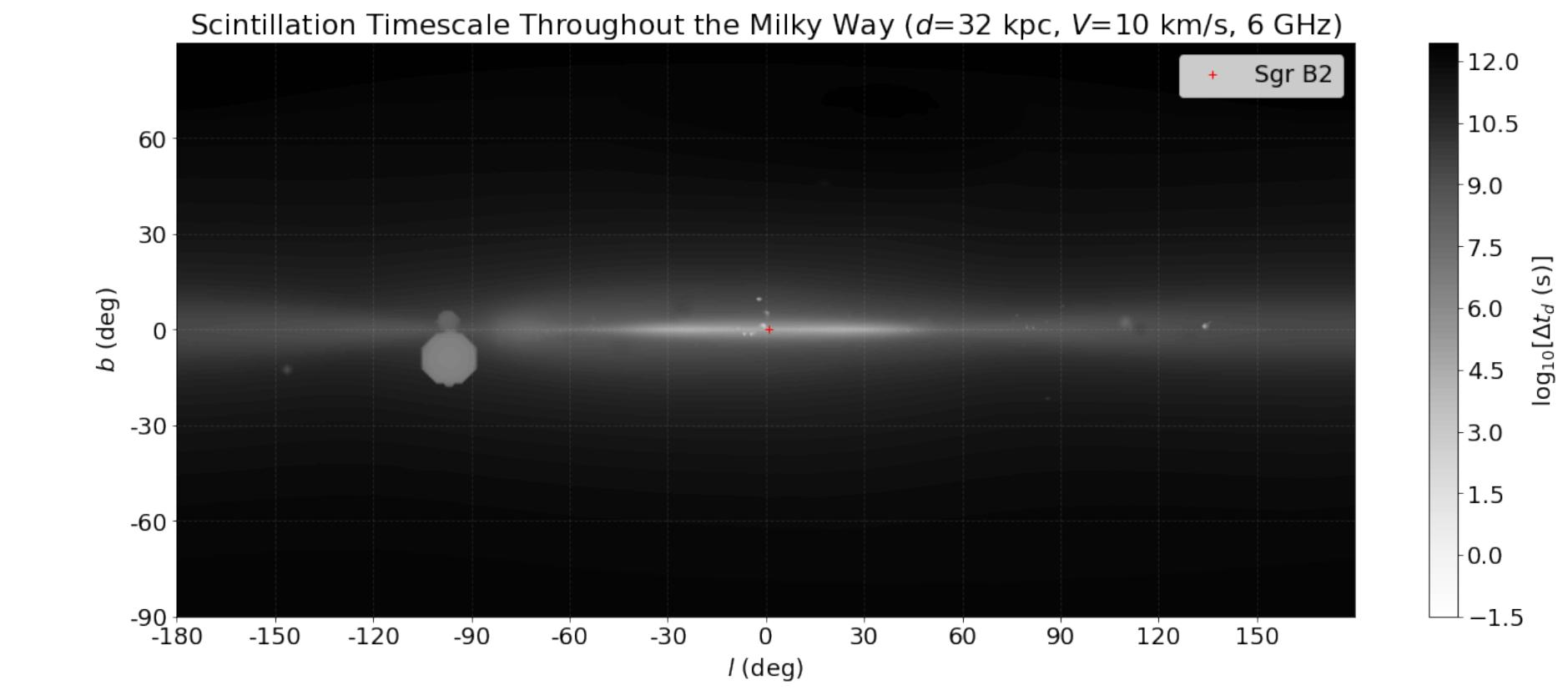
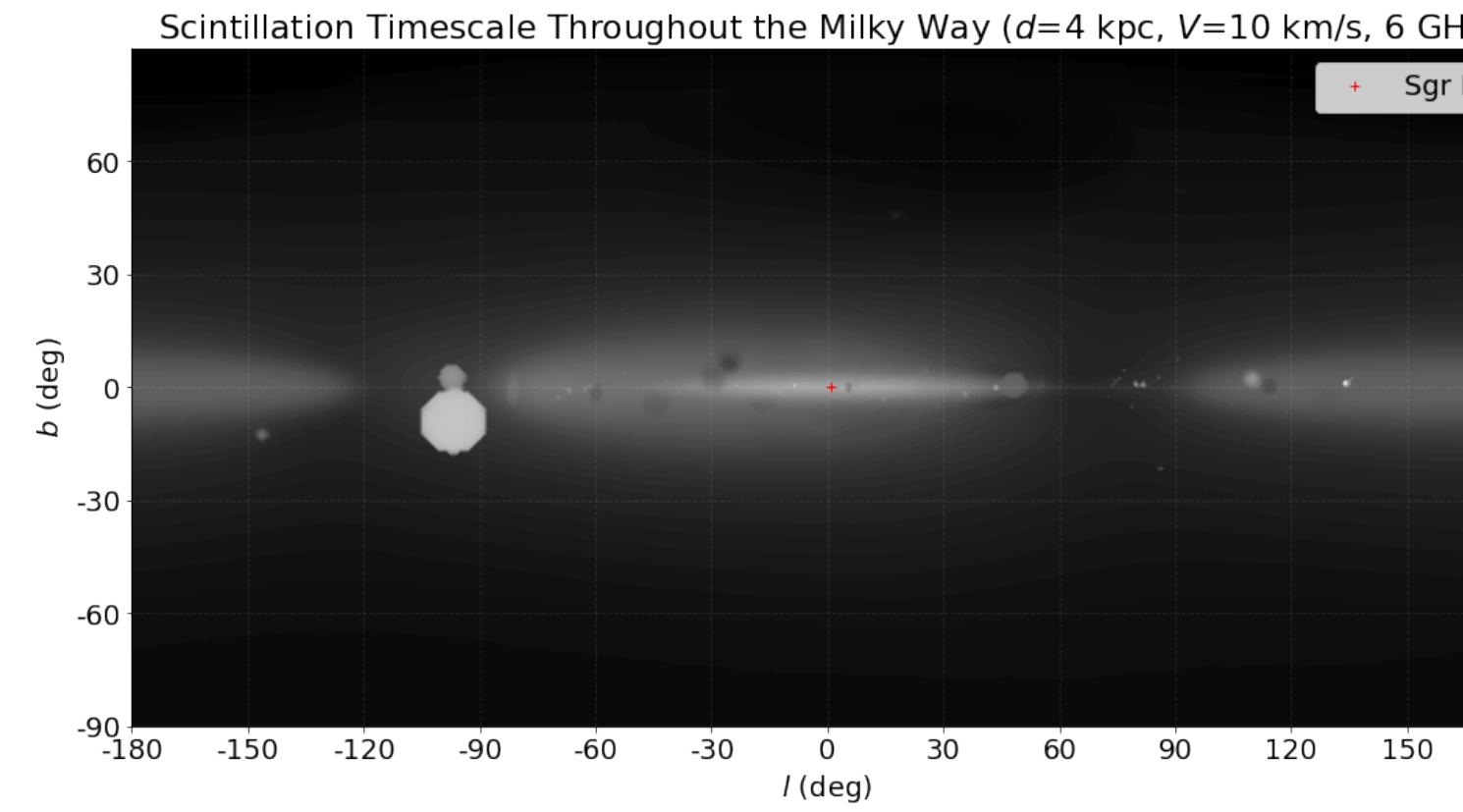
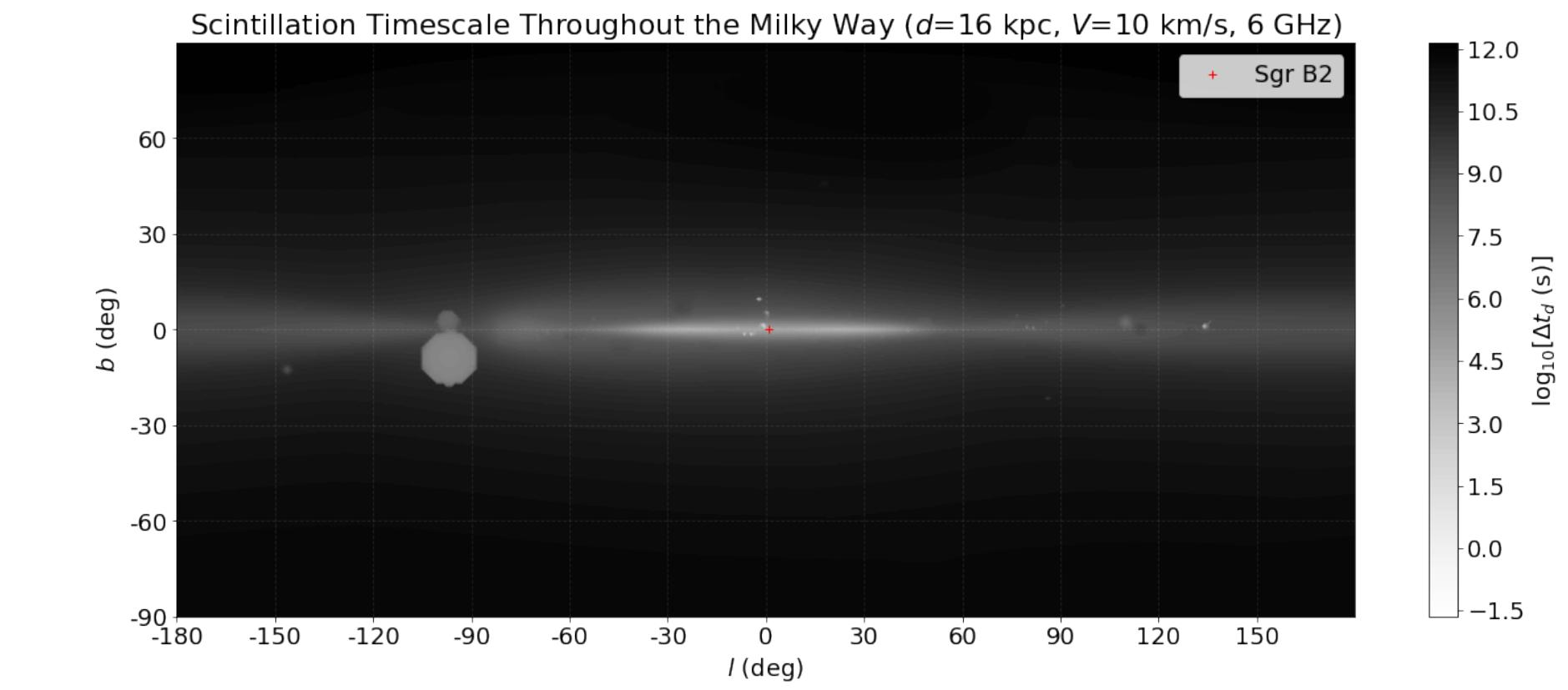
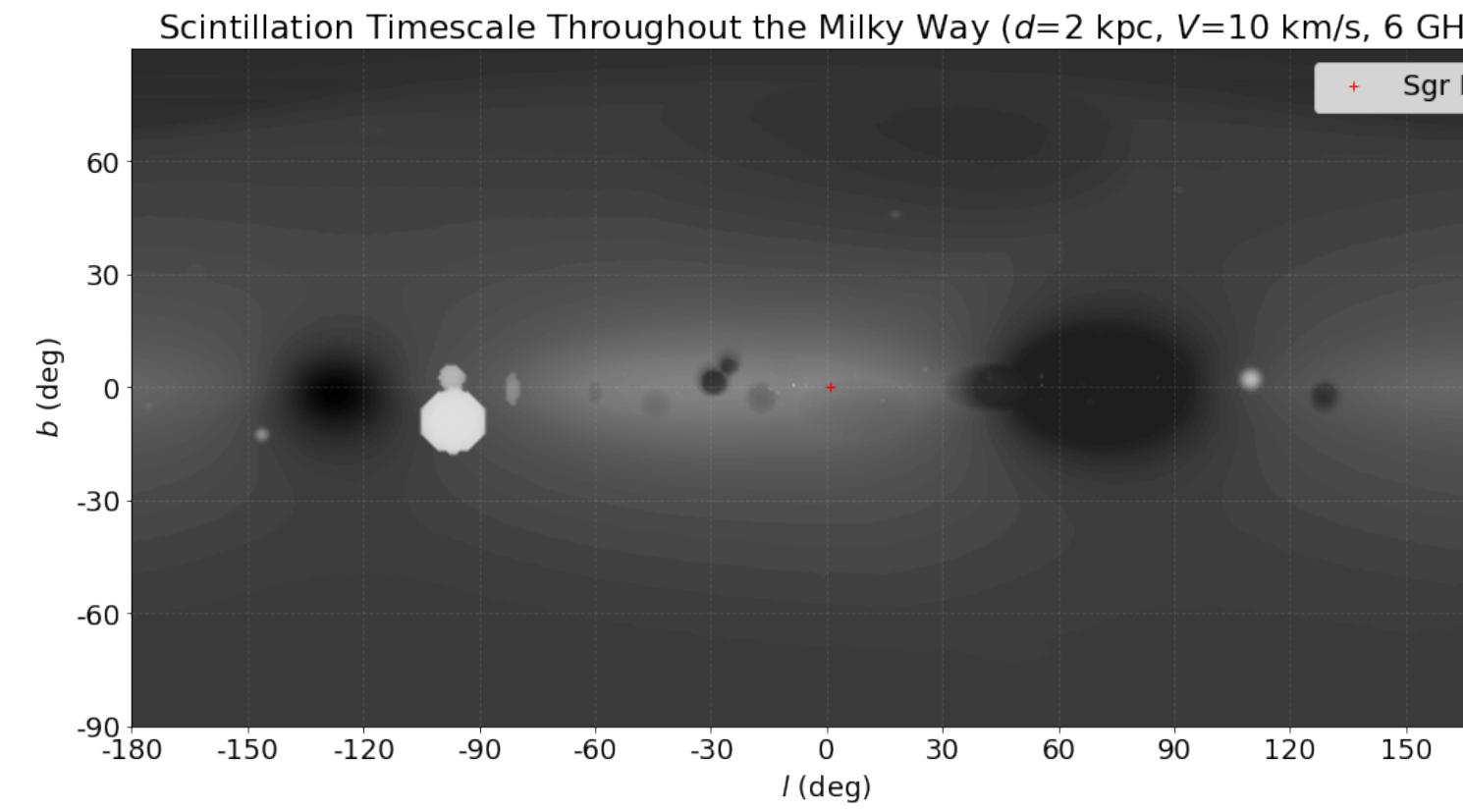
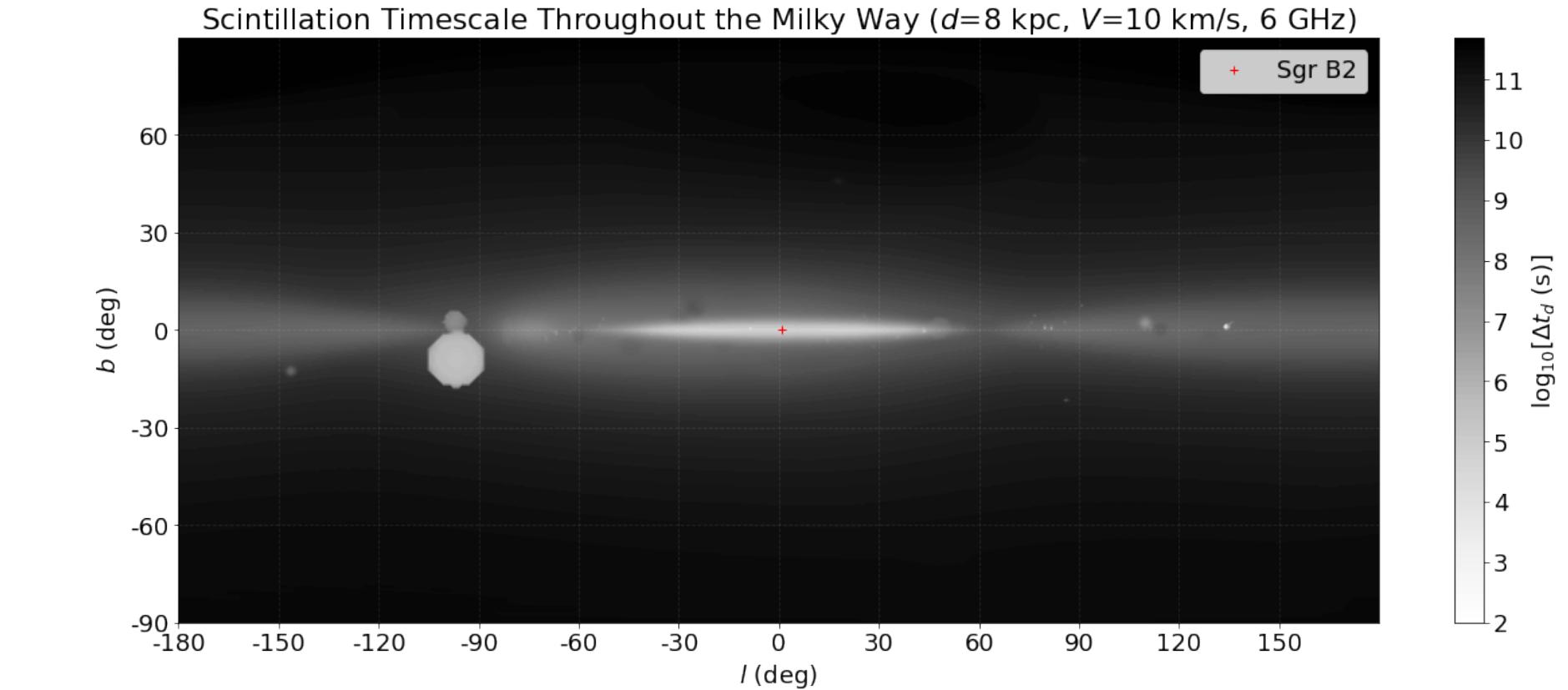
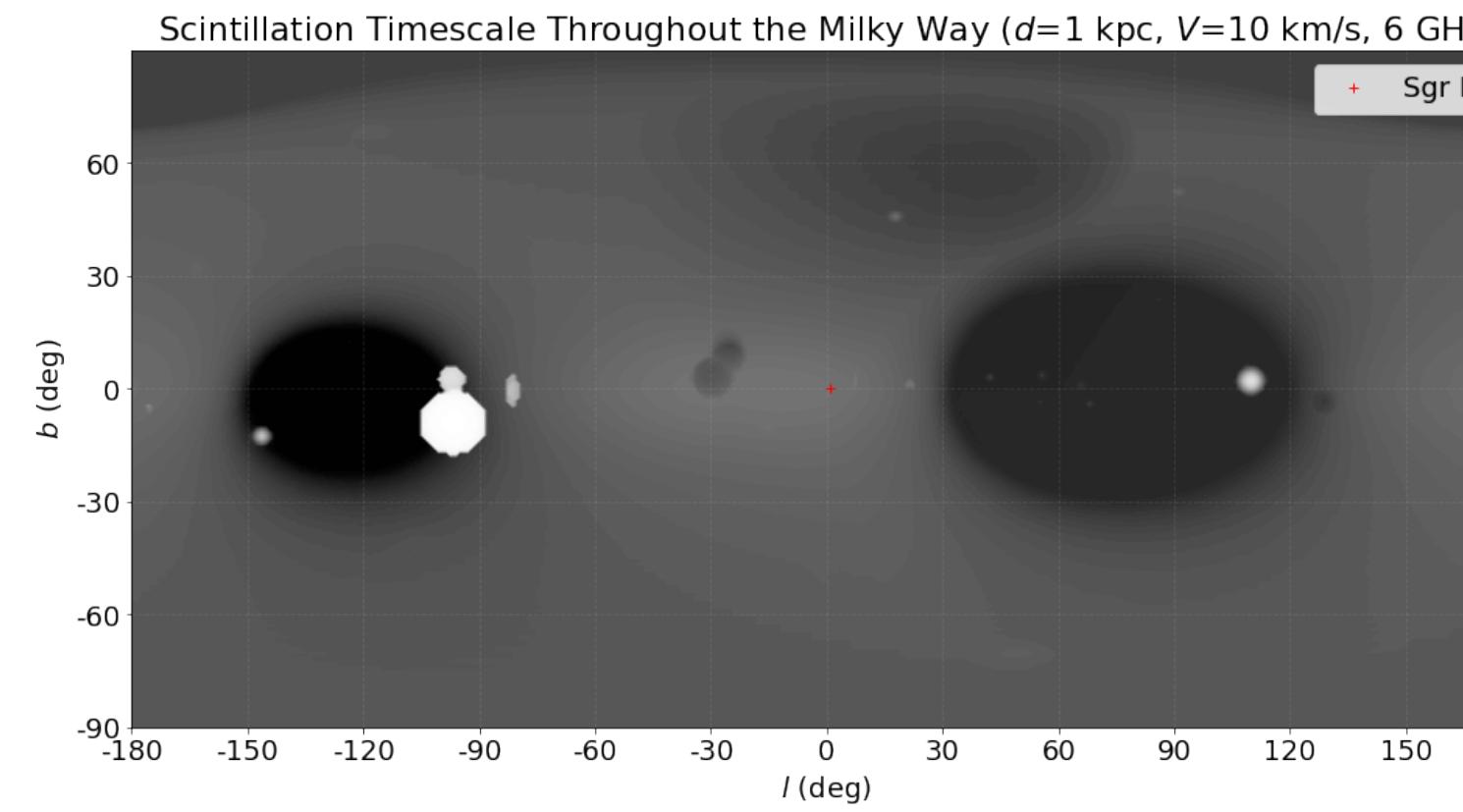
Median



Mode

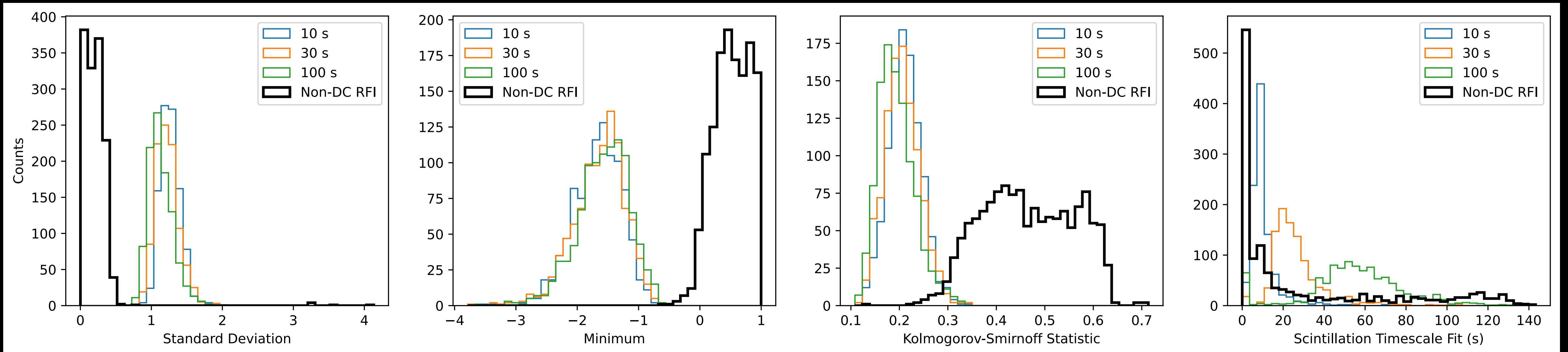


10 s, 30 s, 60 s contours



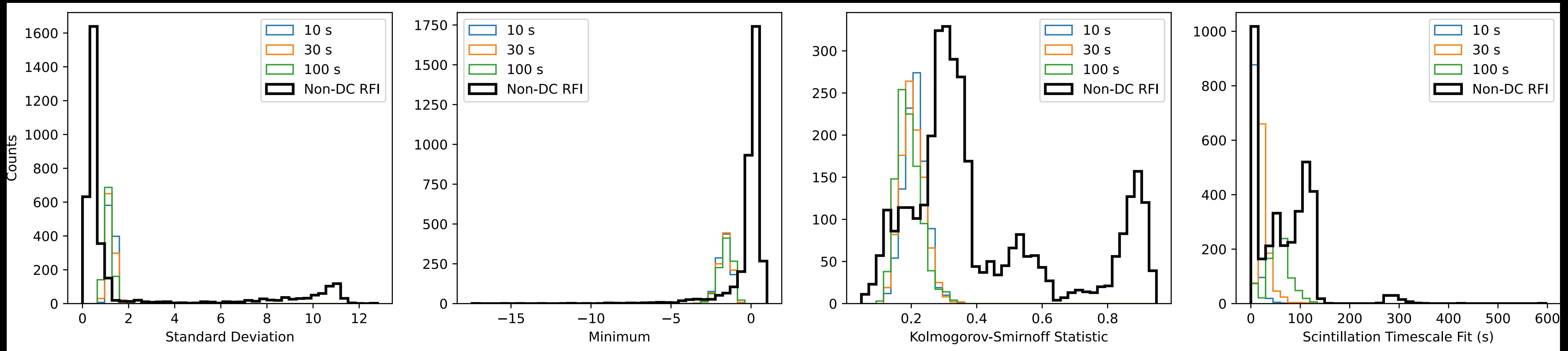
C band

S/N = 10



L band

S/N = 10

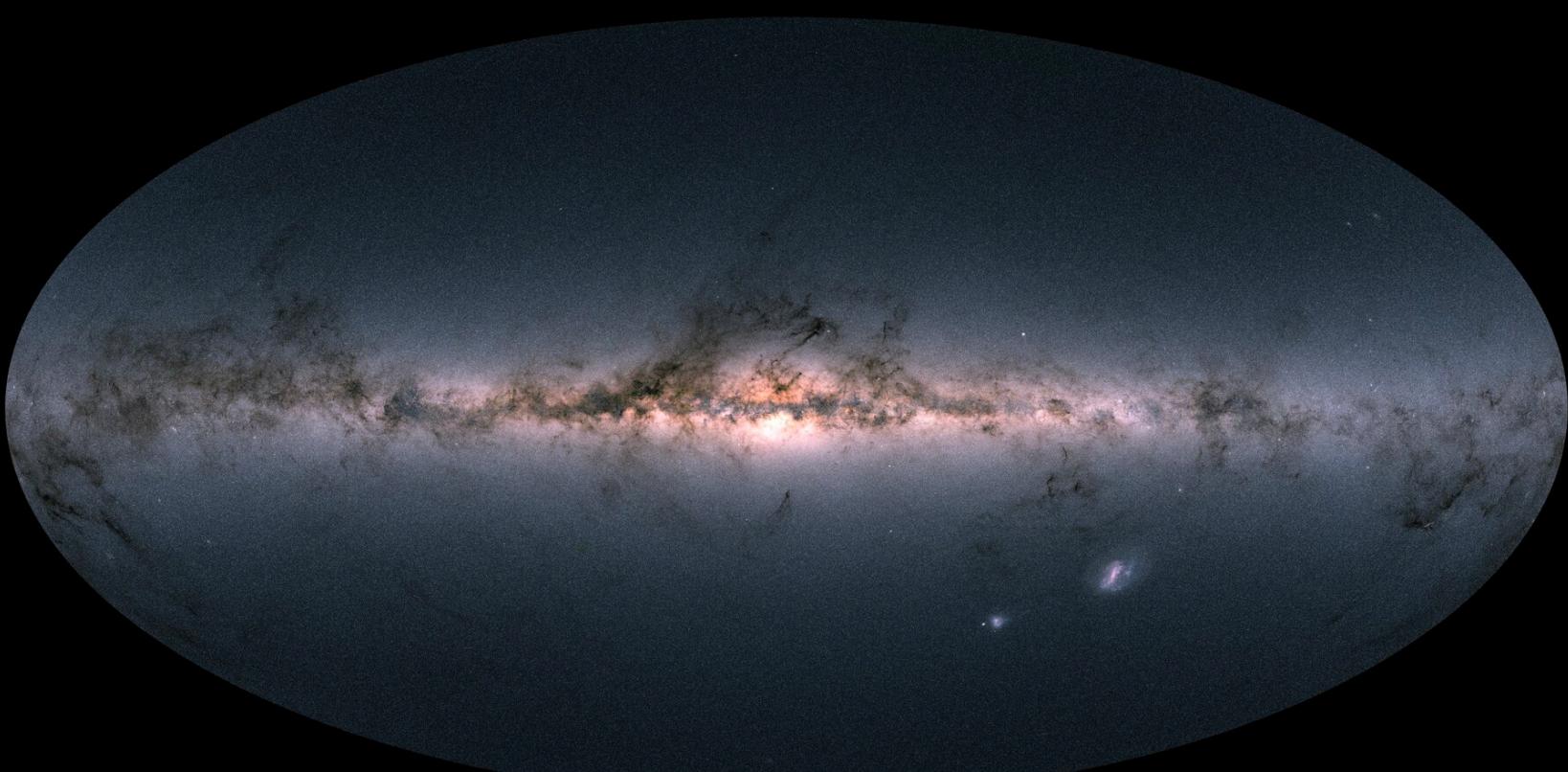
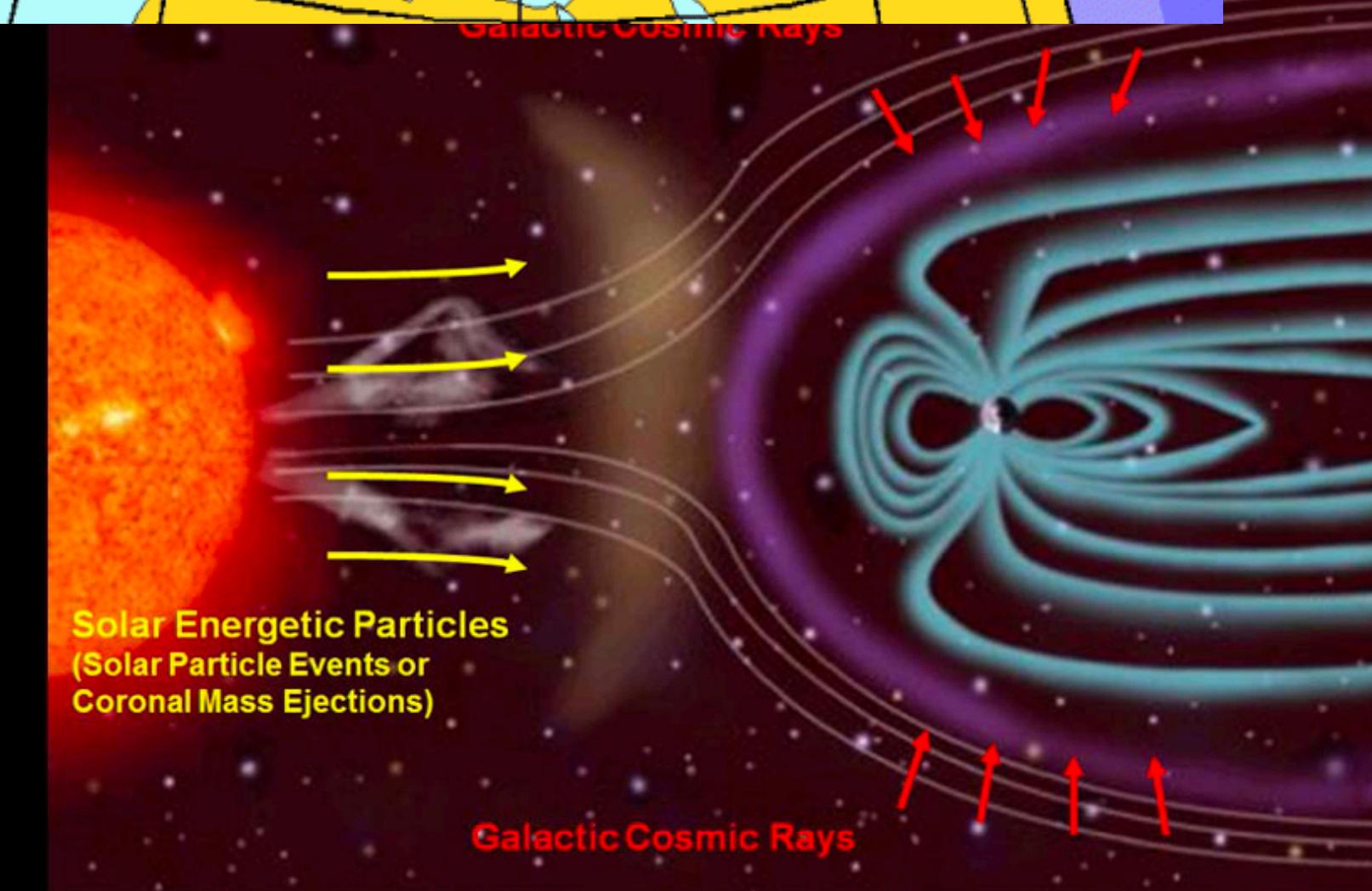
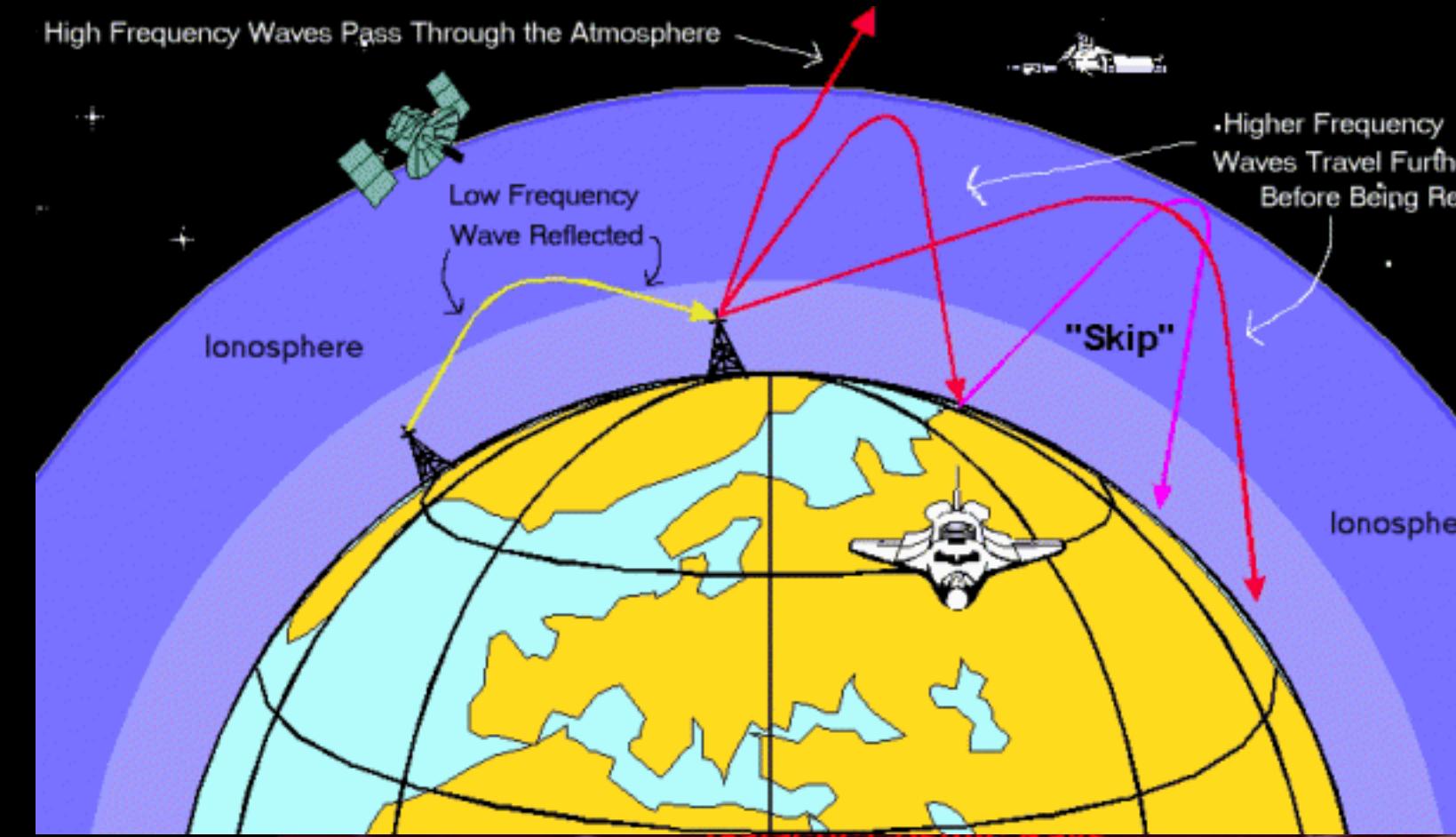


Scattering intensity

- Ionosphere – weak
- IPM – mostly weak
- ISM – can be strong!

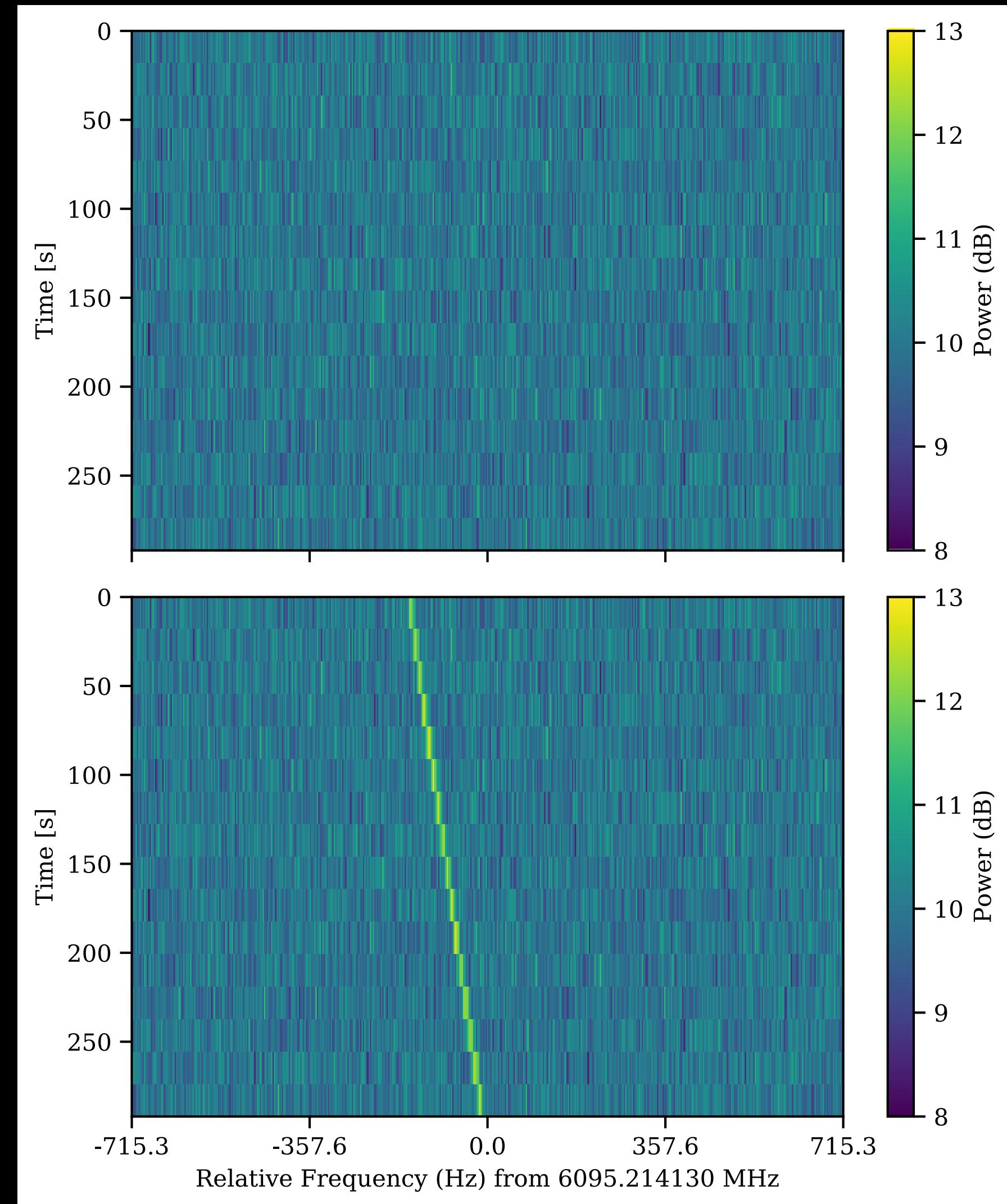
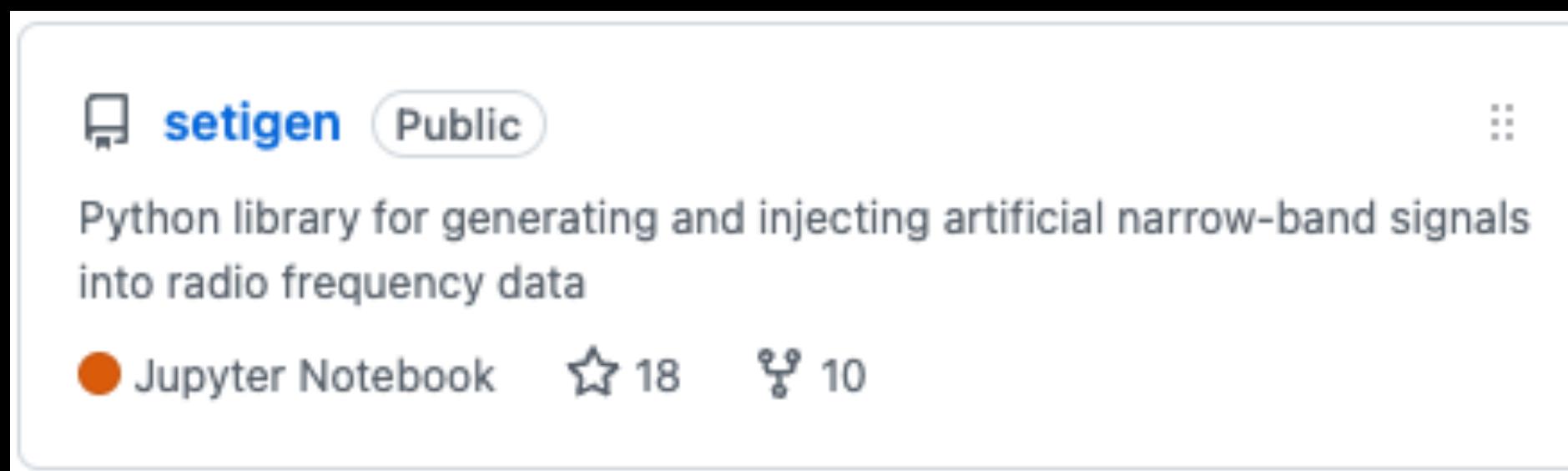
$$m_d \ll 1$$

$$m_d \approx 1$$



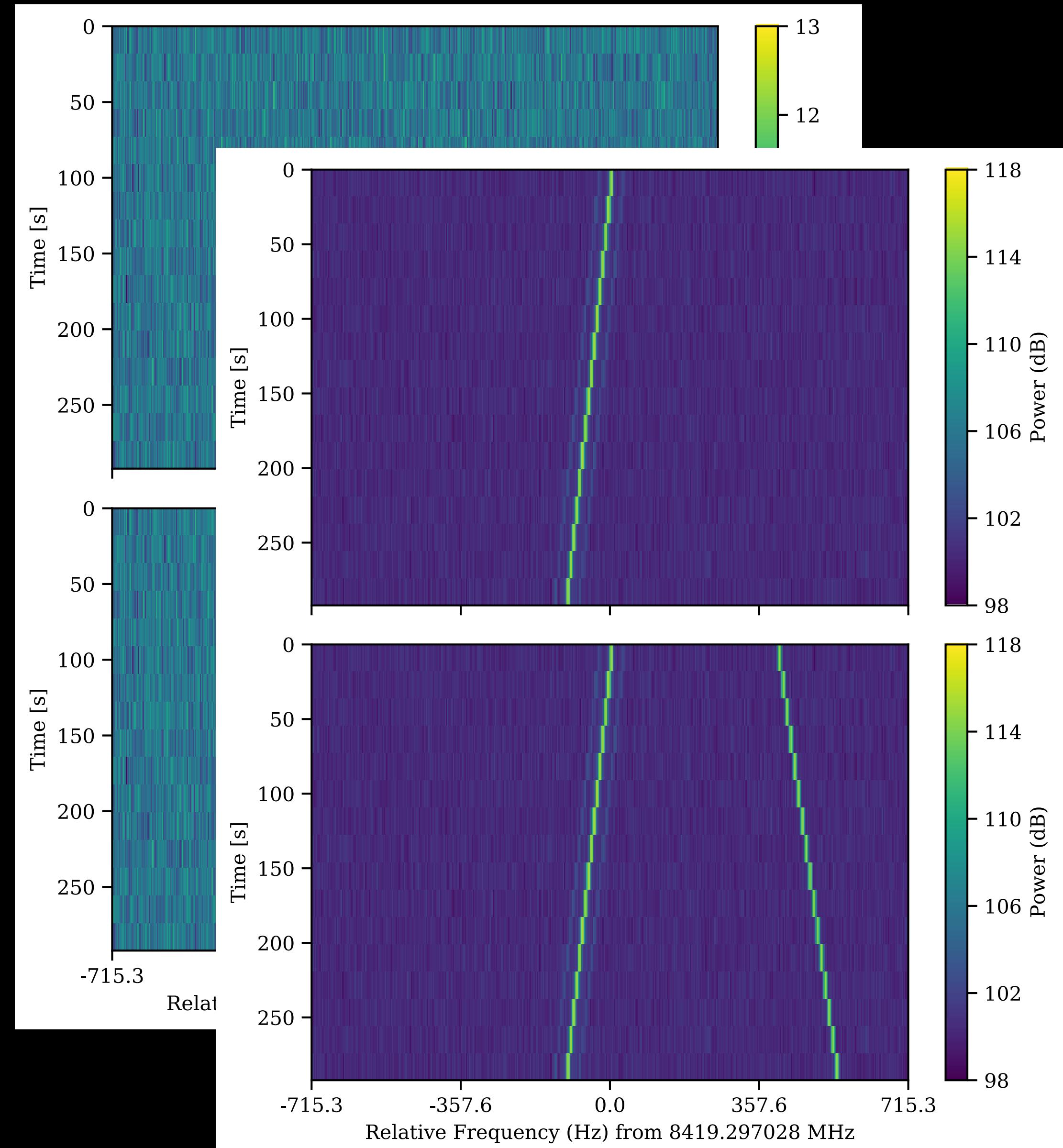
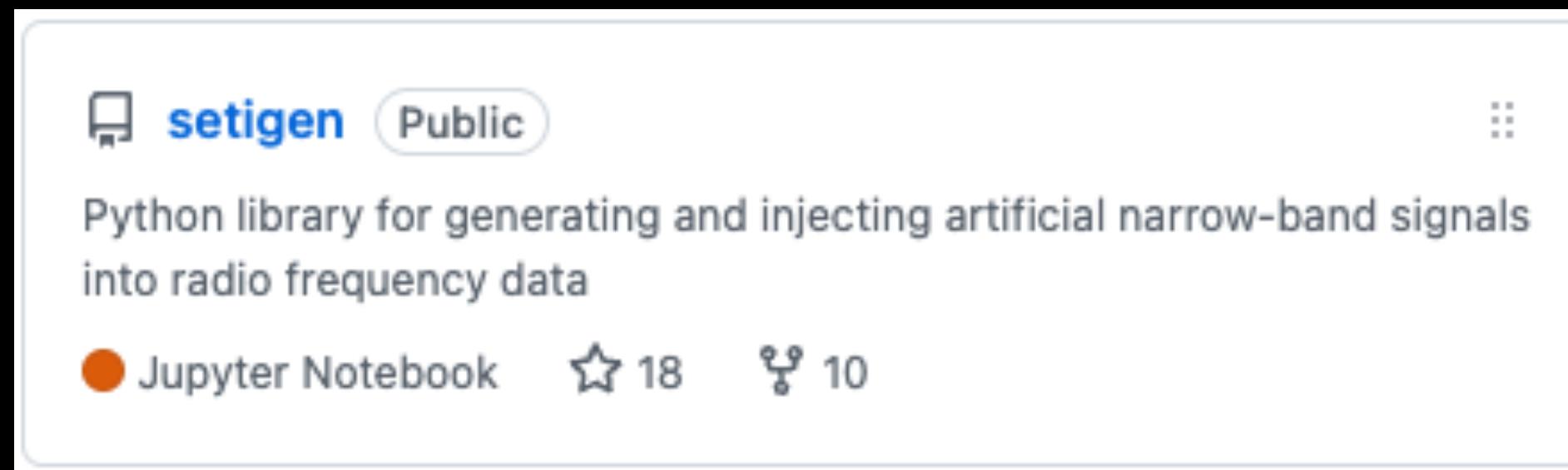
Setigen

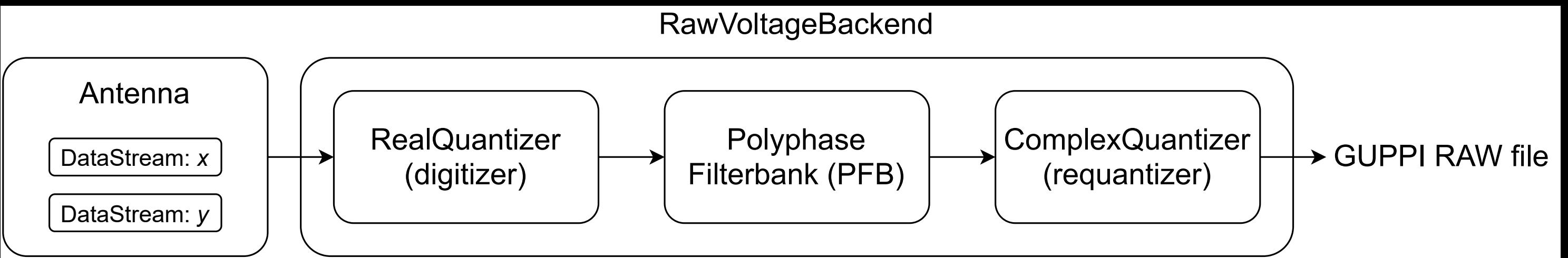
- Python library for synthetic spectrogram and voltage data
- Specific focus on narrowband signal generation and injection



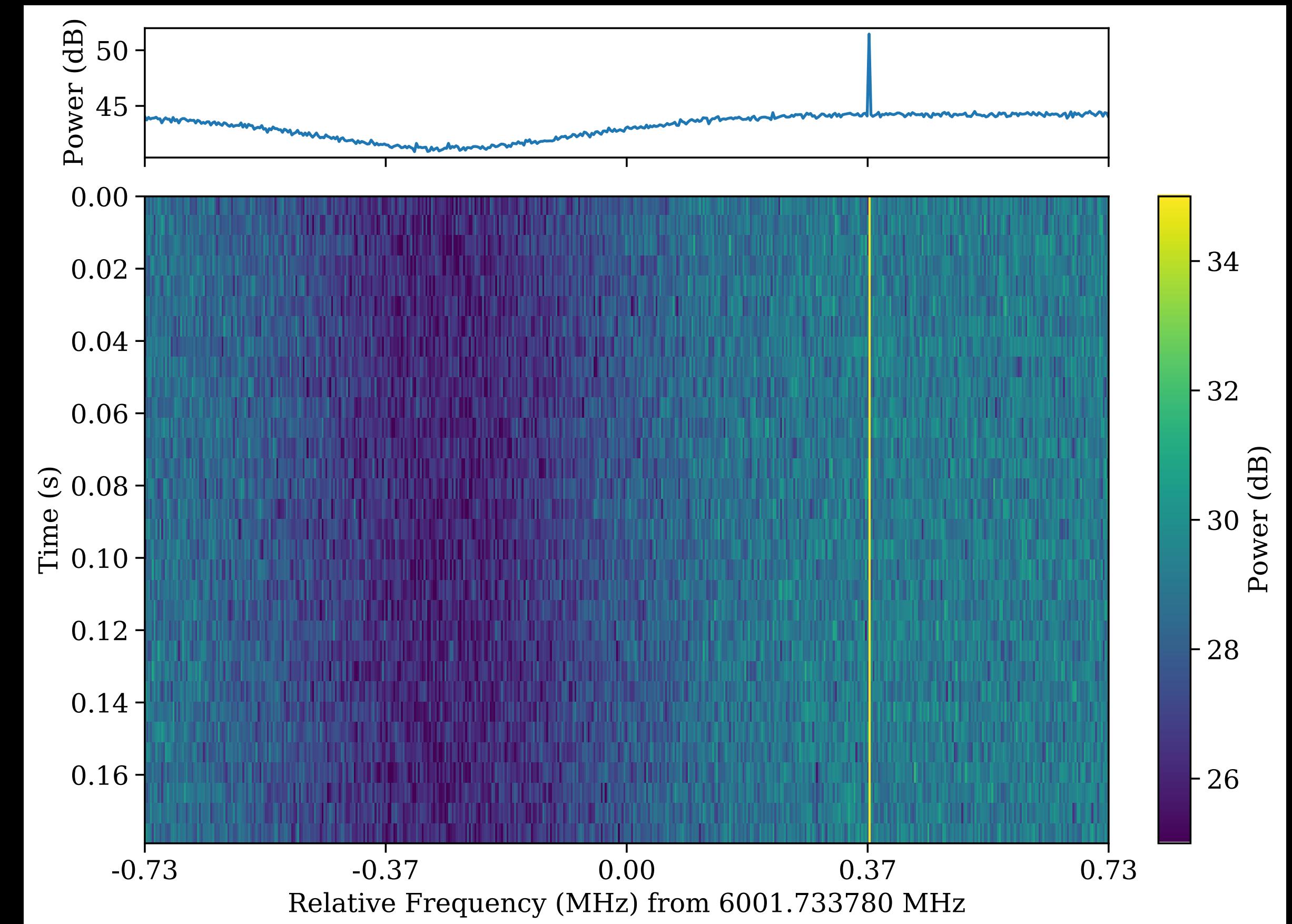
Setigen

- Python library for synthetic spectrogram and voltage data
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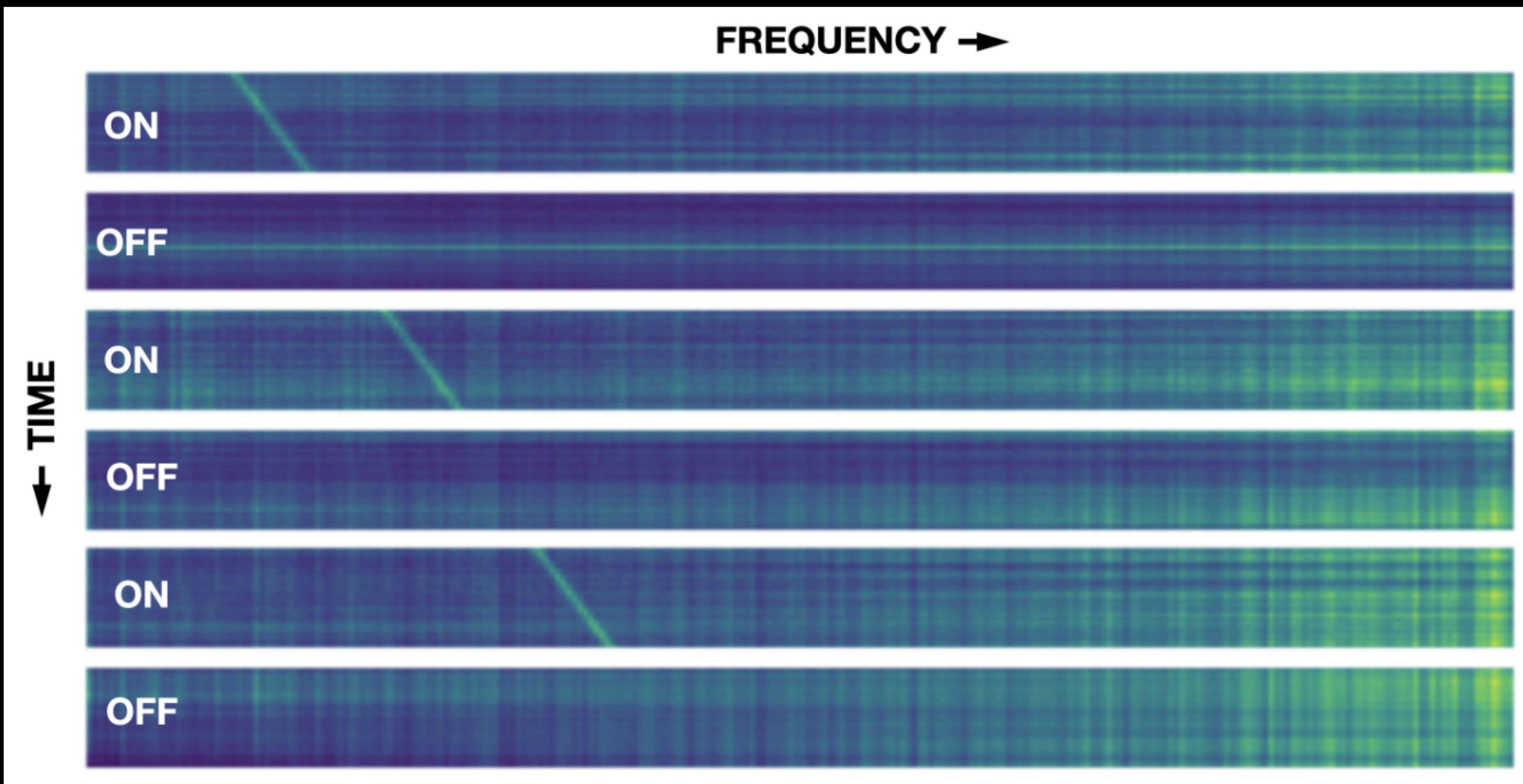


- Synthetic complex voltage data
- Simple models of backend components, such as a polyphase filterbank



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



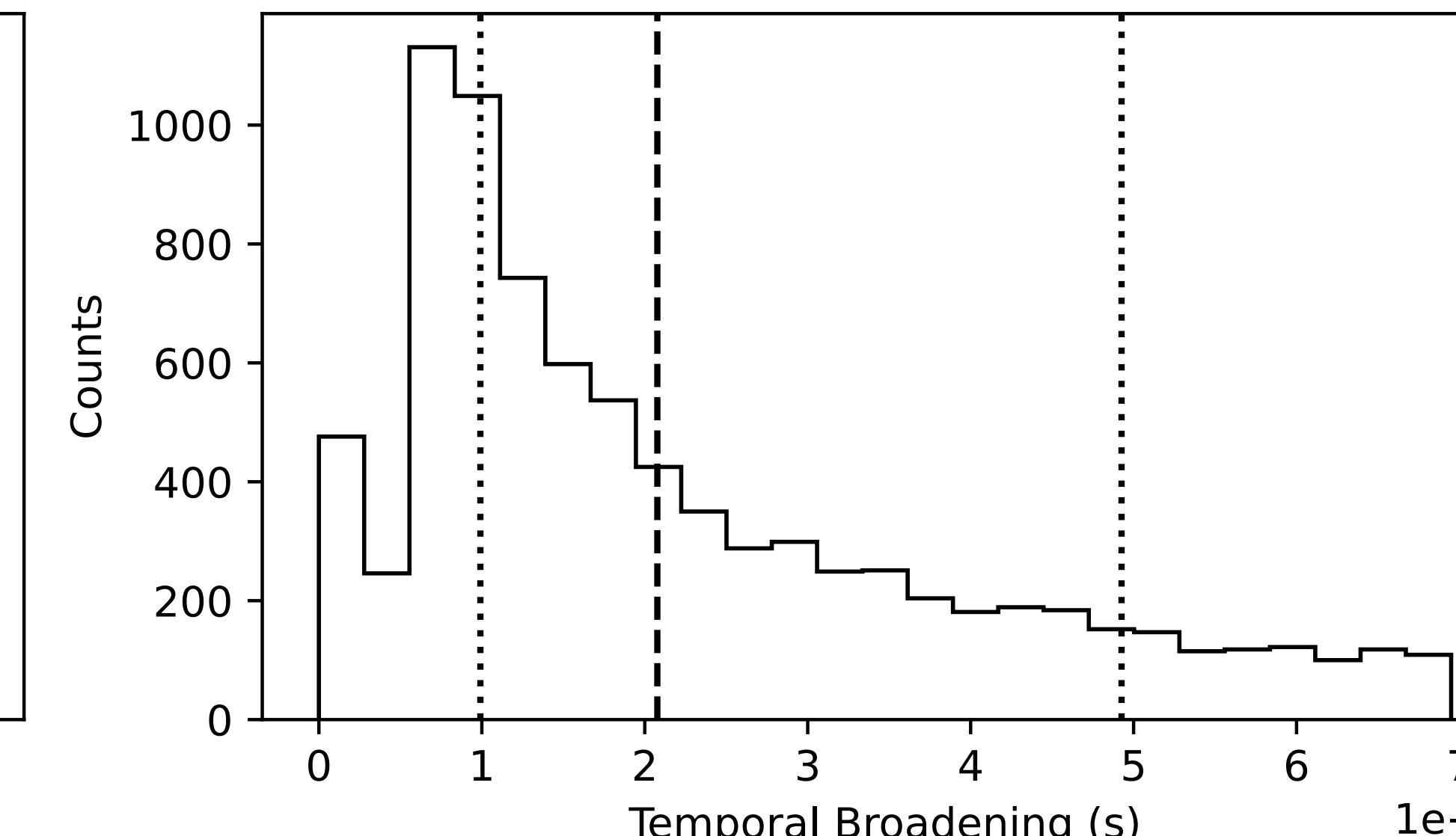
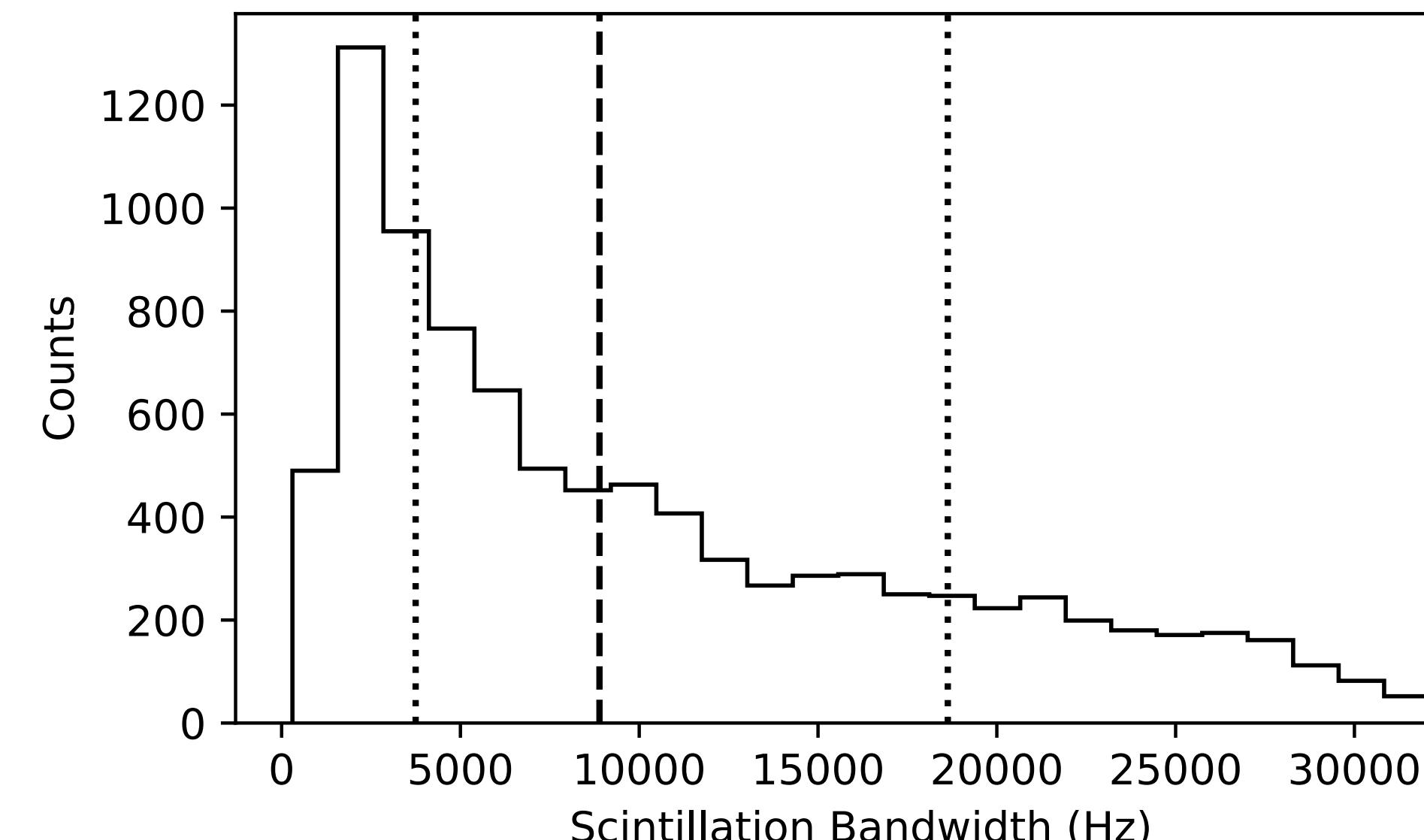
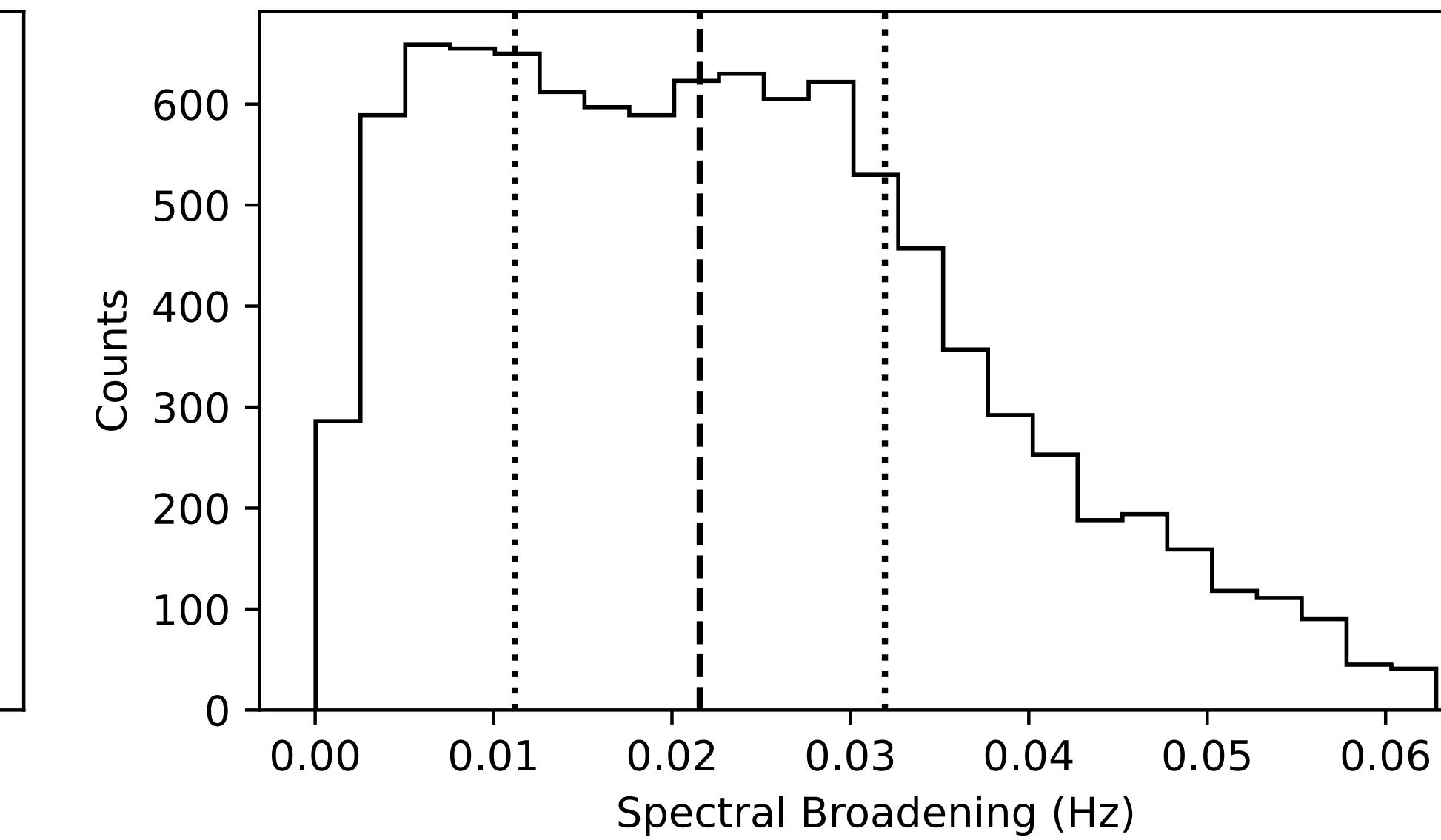
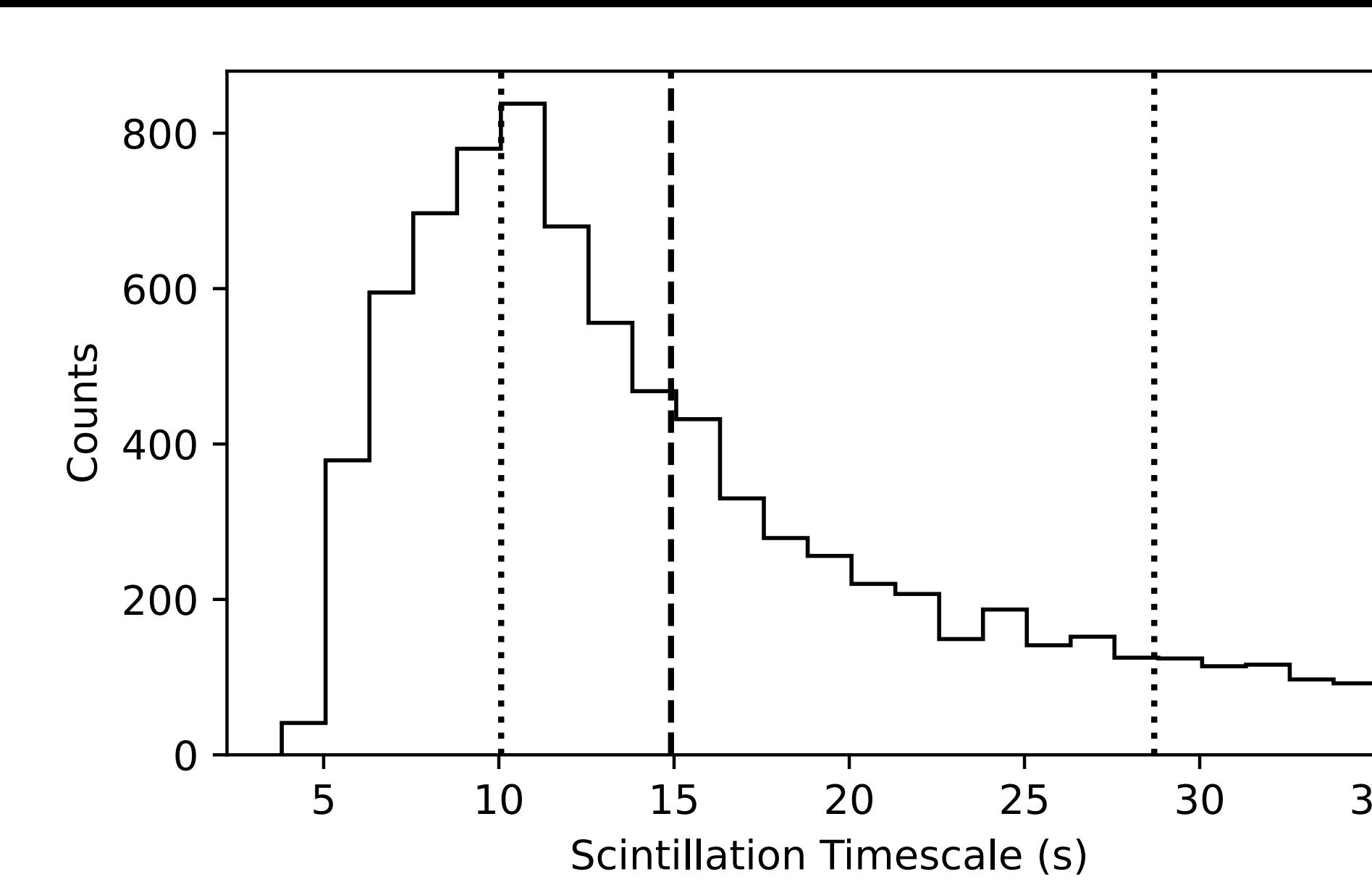
Breakthrough Listen x Kaggle 2021

Inter-quartile range

Median

C-band

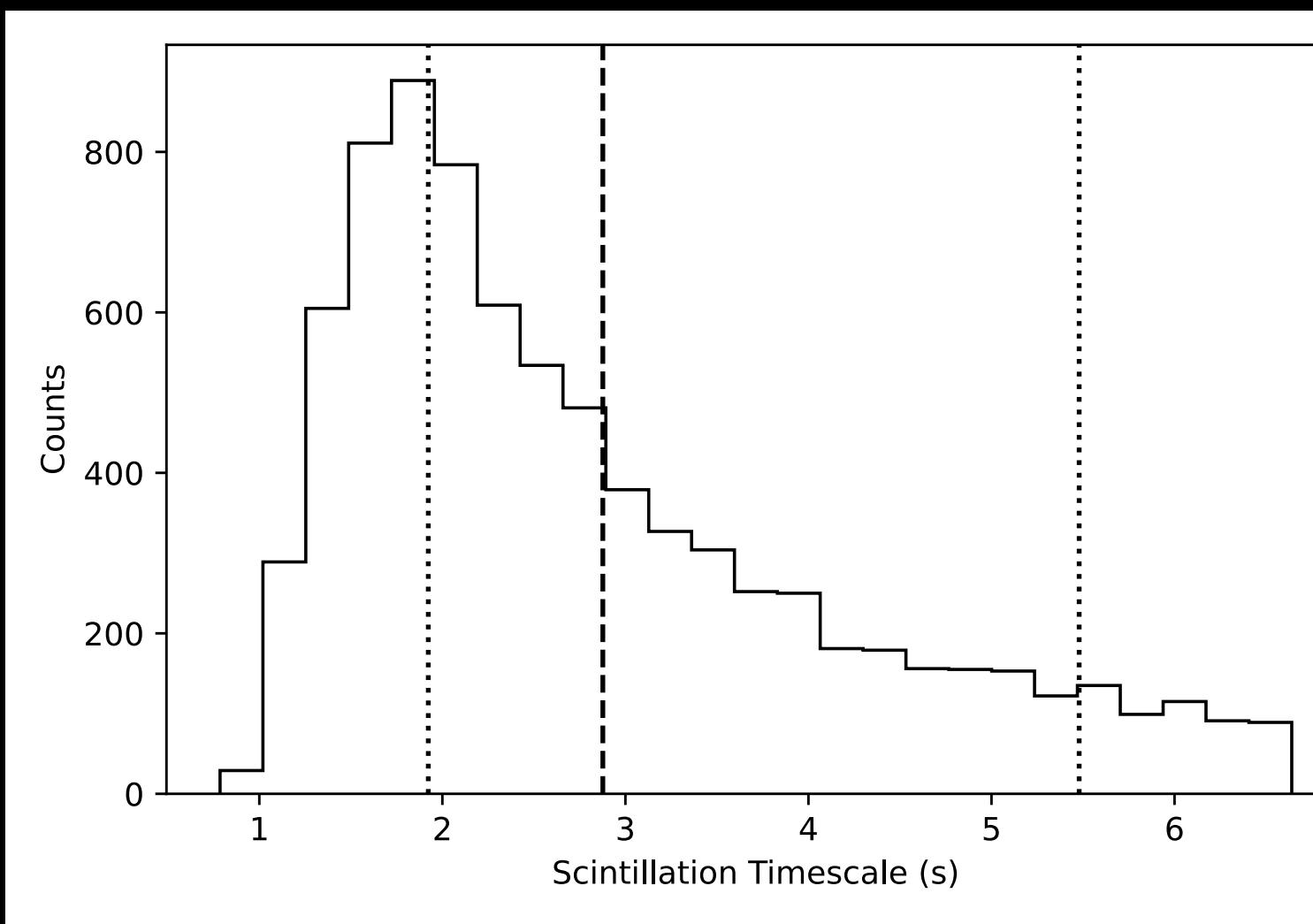
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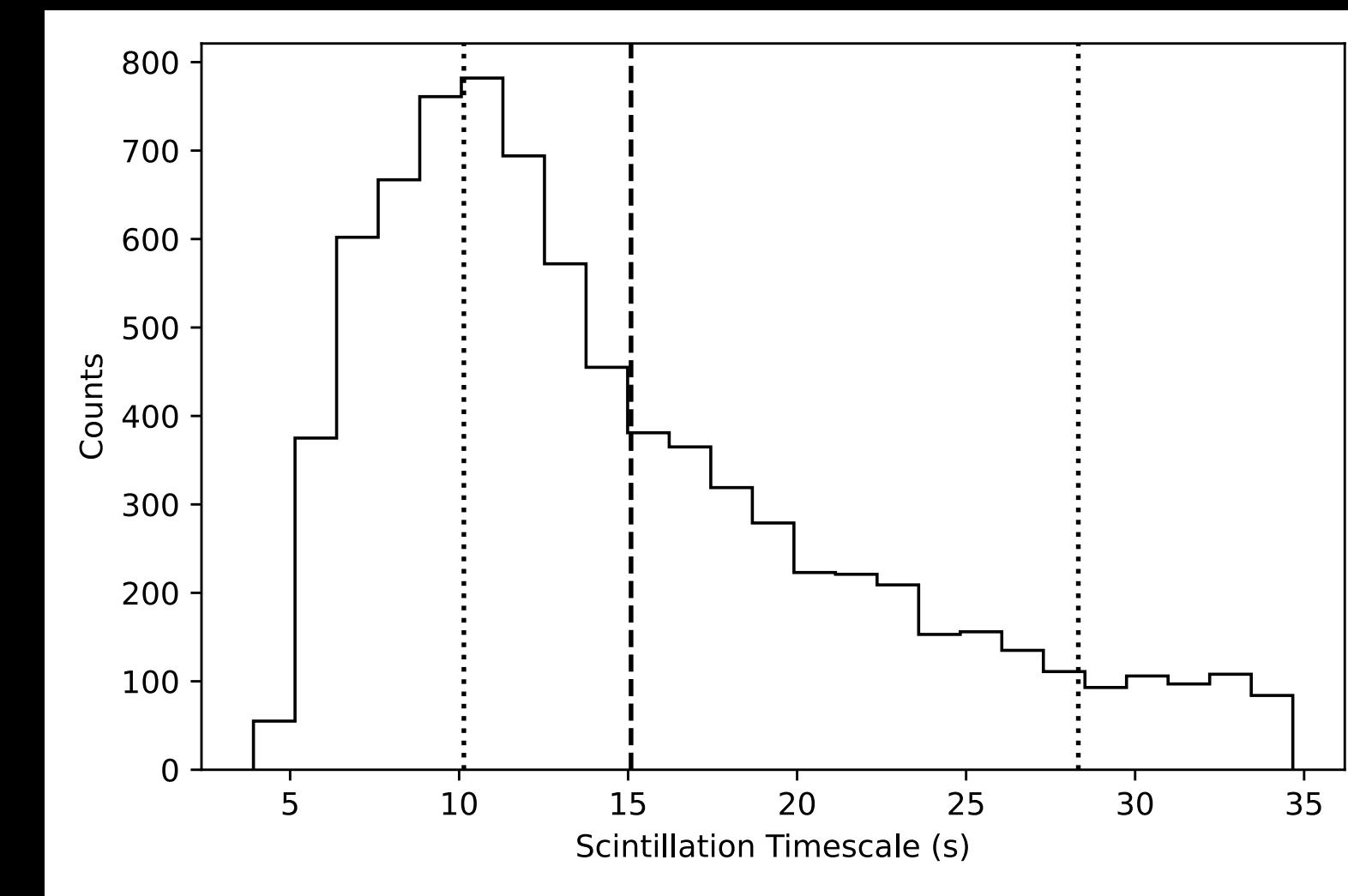
Monte Carlo-sampled timescales

Density

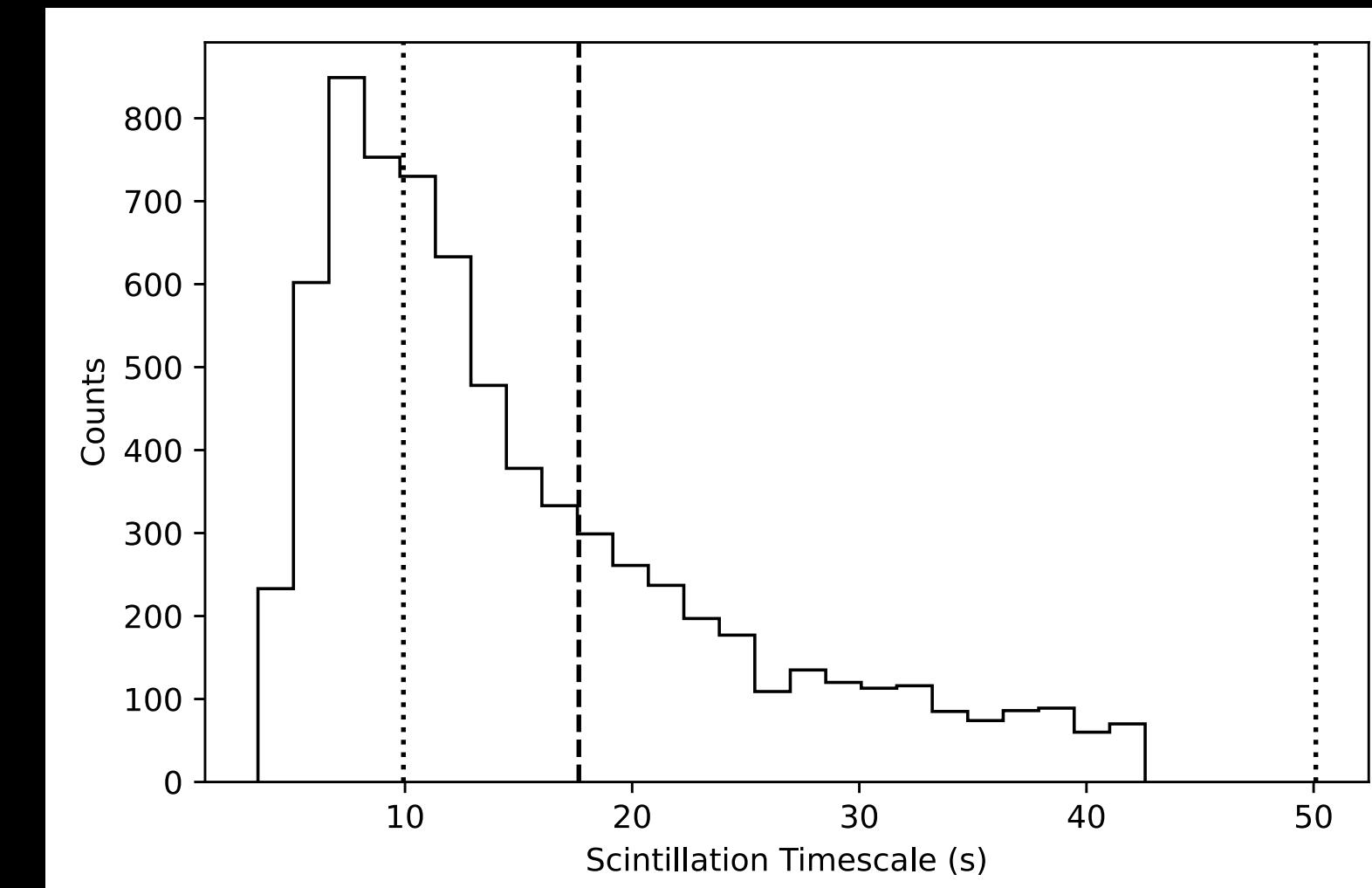
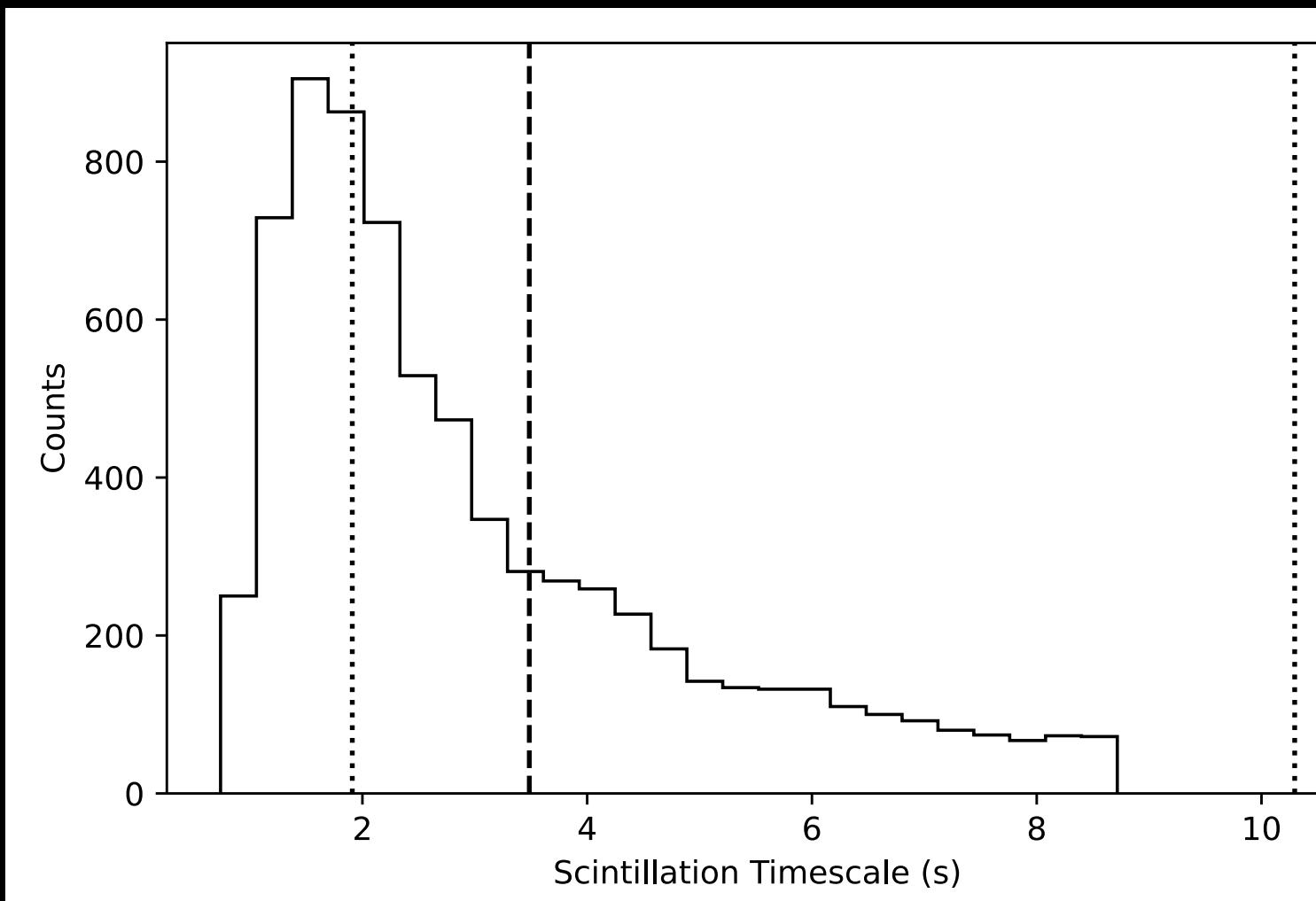
L band



C band



Uniform



Statistics at different bands

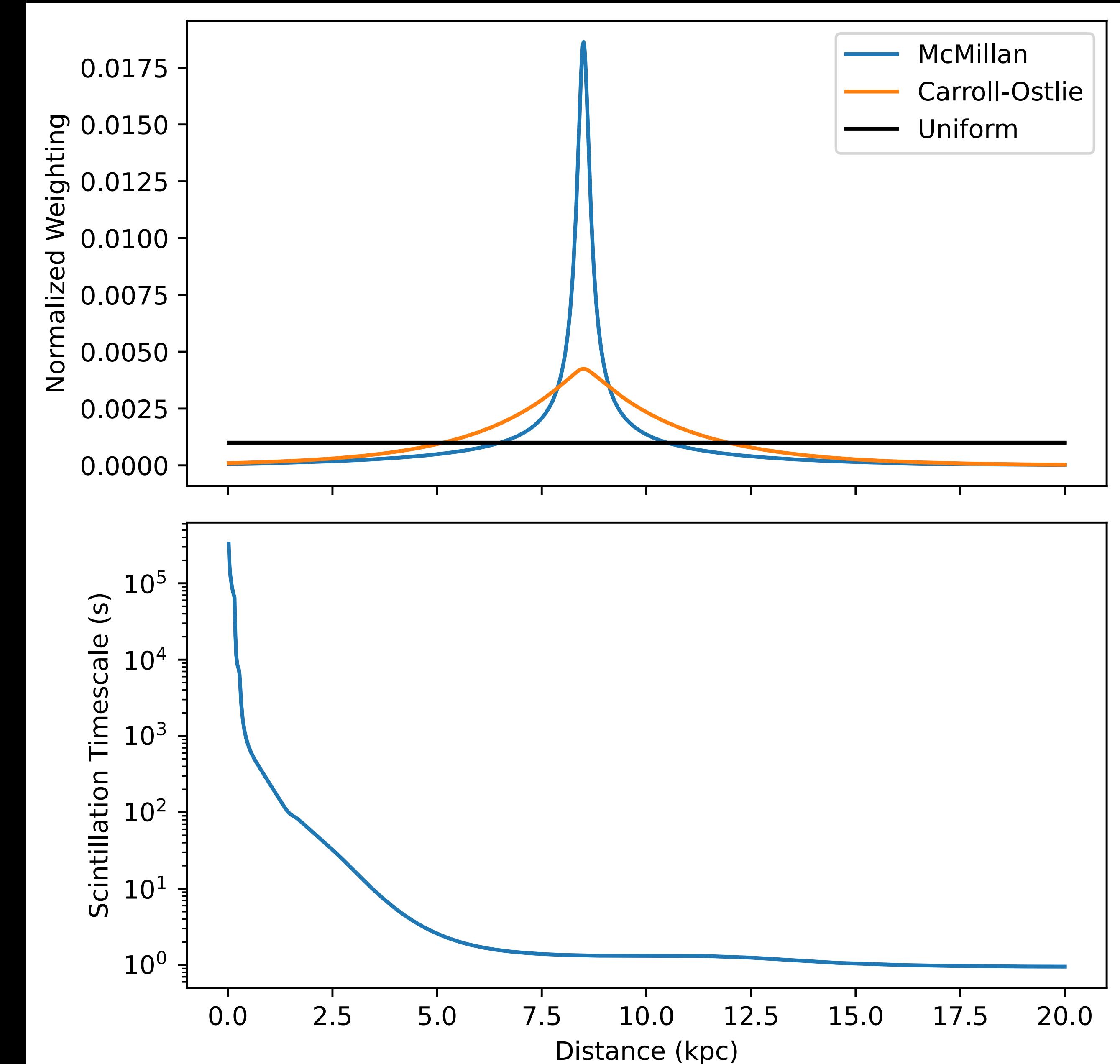
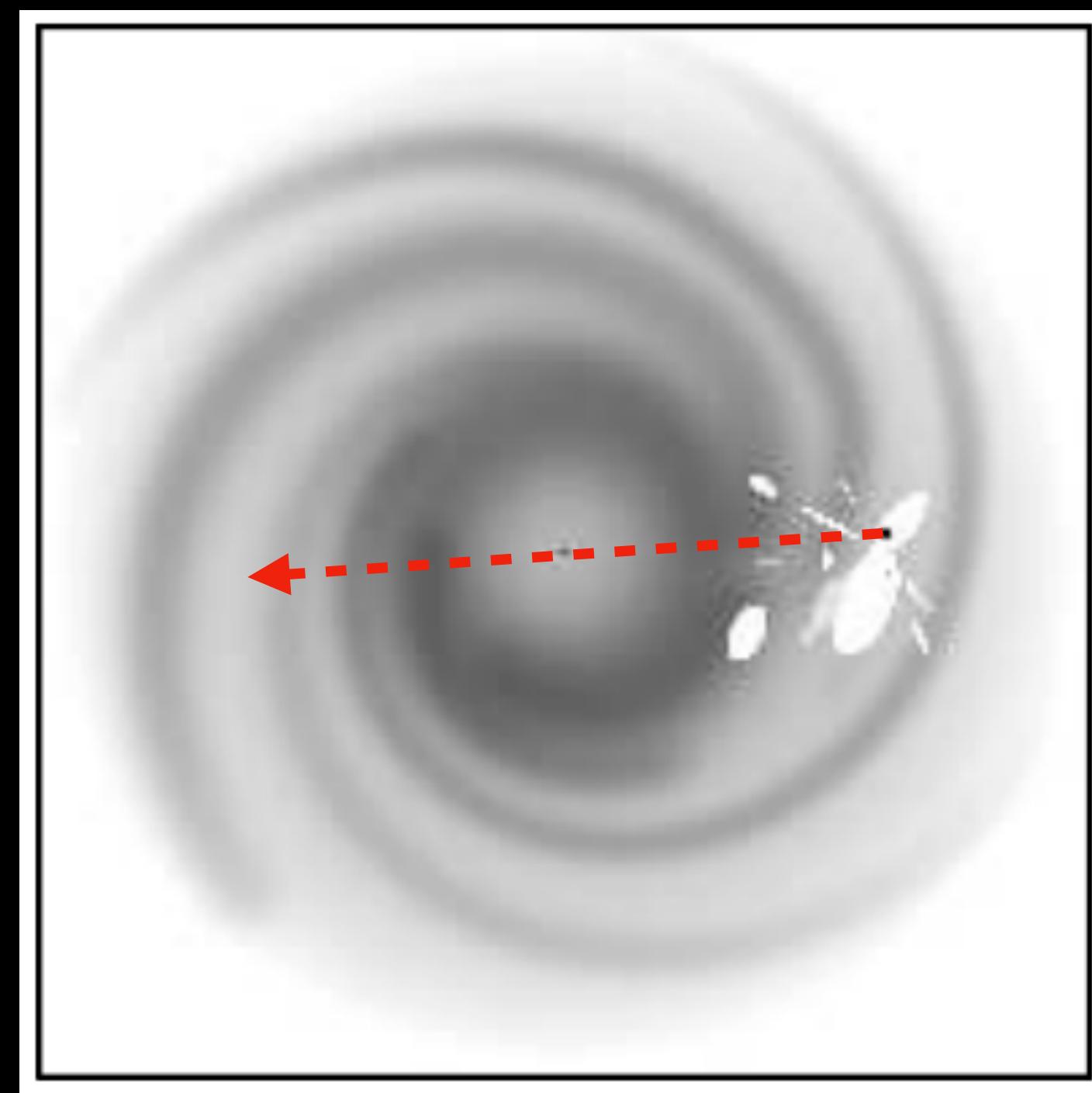
$$(l, b) = (1, 0)$$

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

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

$(l, b) = (1, 0)$

Density-based sampling

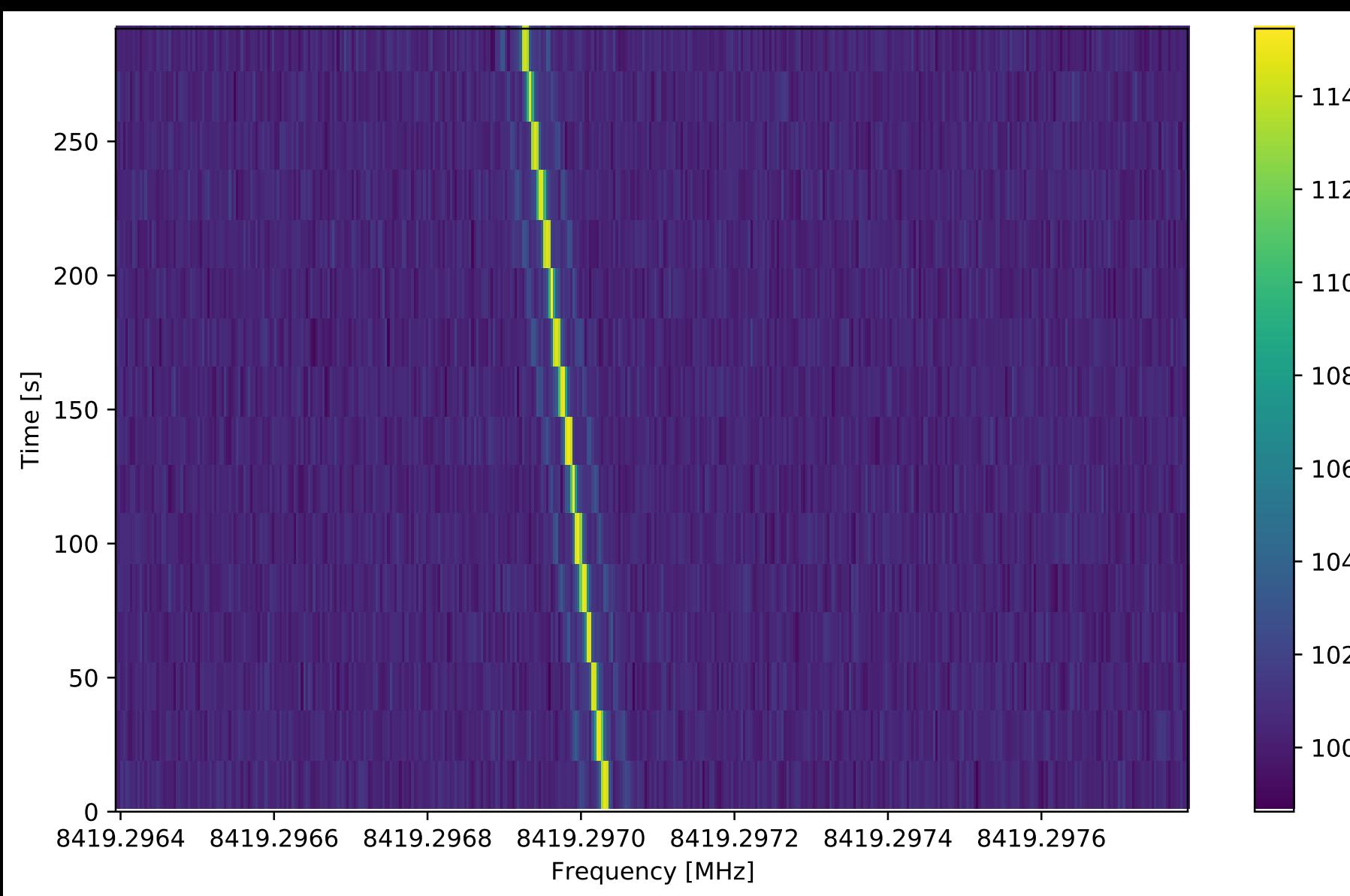


What would strongly scattered signals look like?

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

What would strongly scattered signals look like?

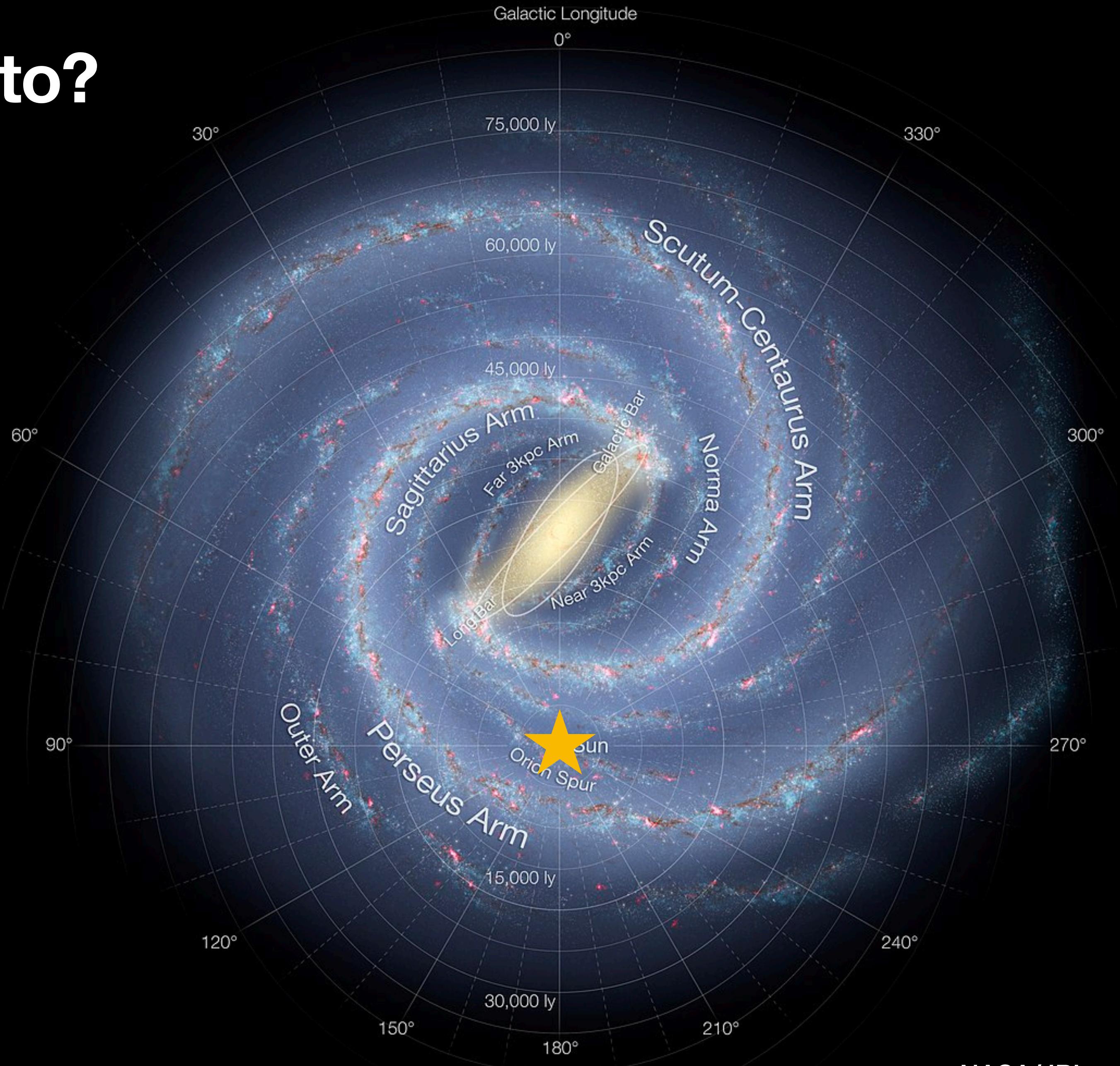
- Assuming a 100% duty-cycle narrowband transmitter



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

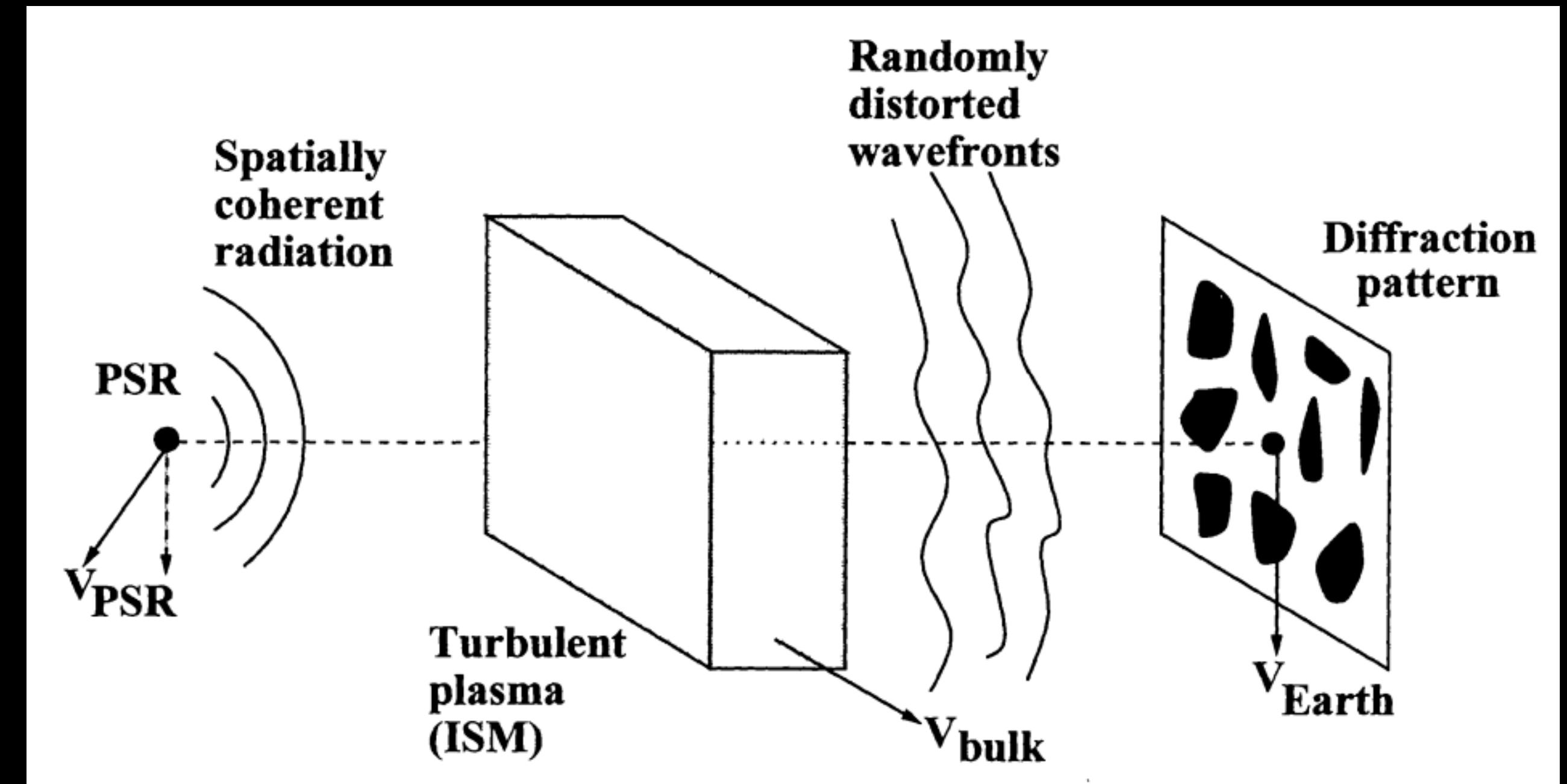
Why is this worth looking into?

- 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



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

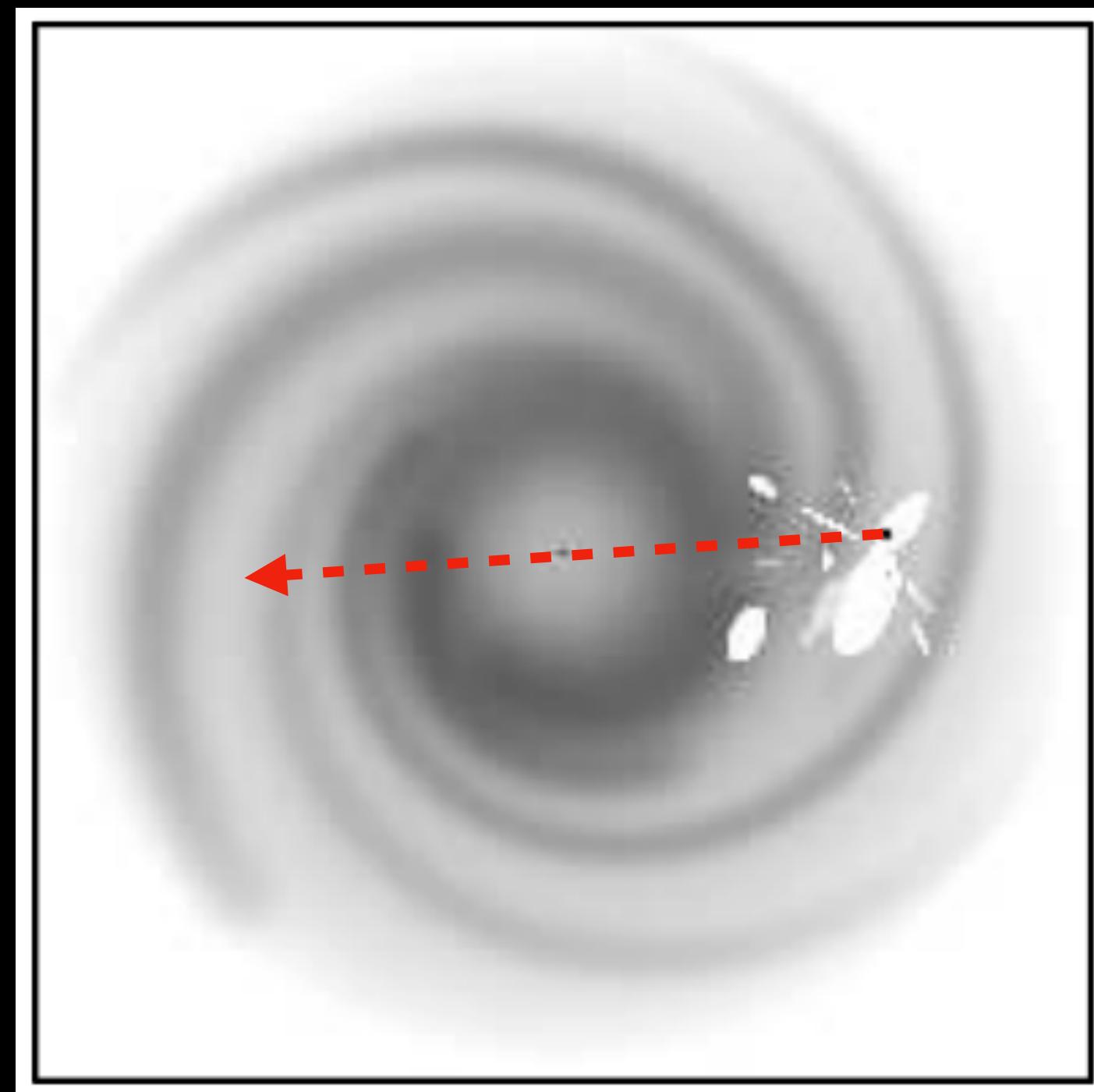
- A priori, we do not know:
 - Sky direction
 - Frequency
 - Distance
 - Transverse velocity

Monte Carlo sampling!

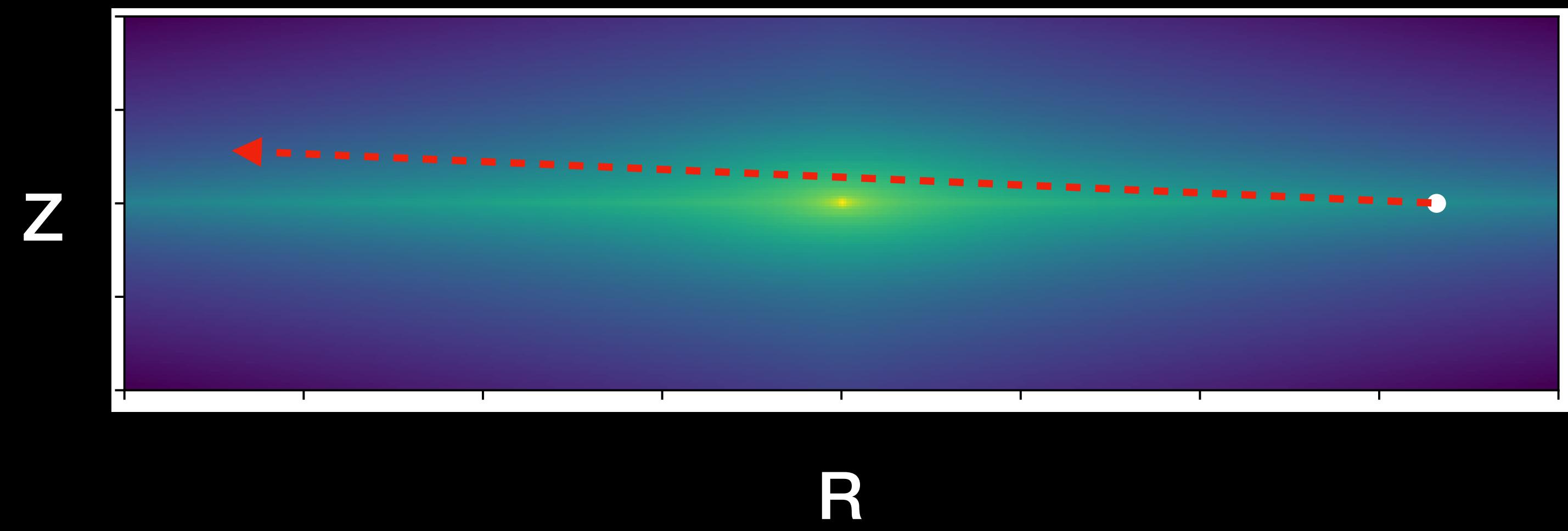
$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$

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

Density-based sampling

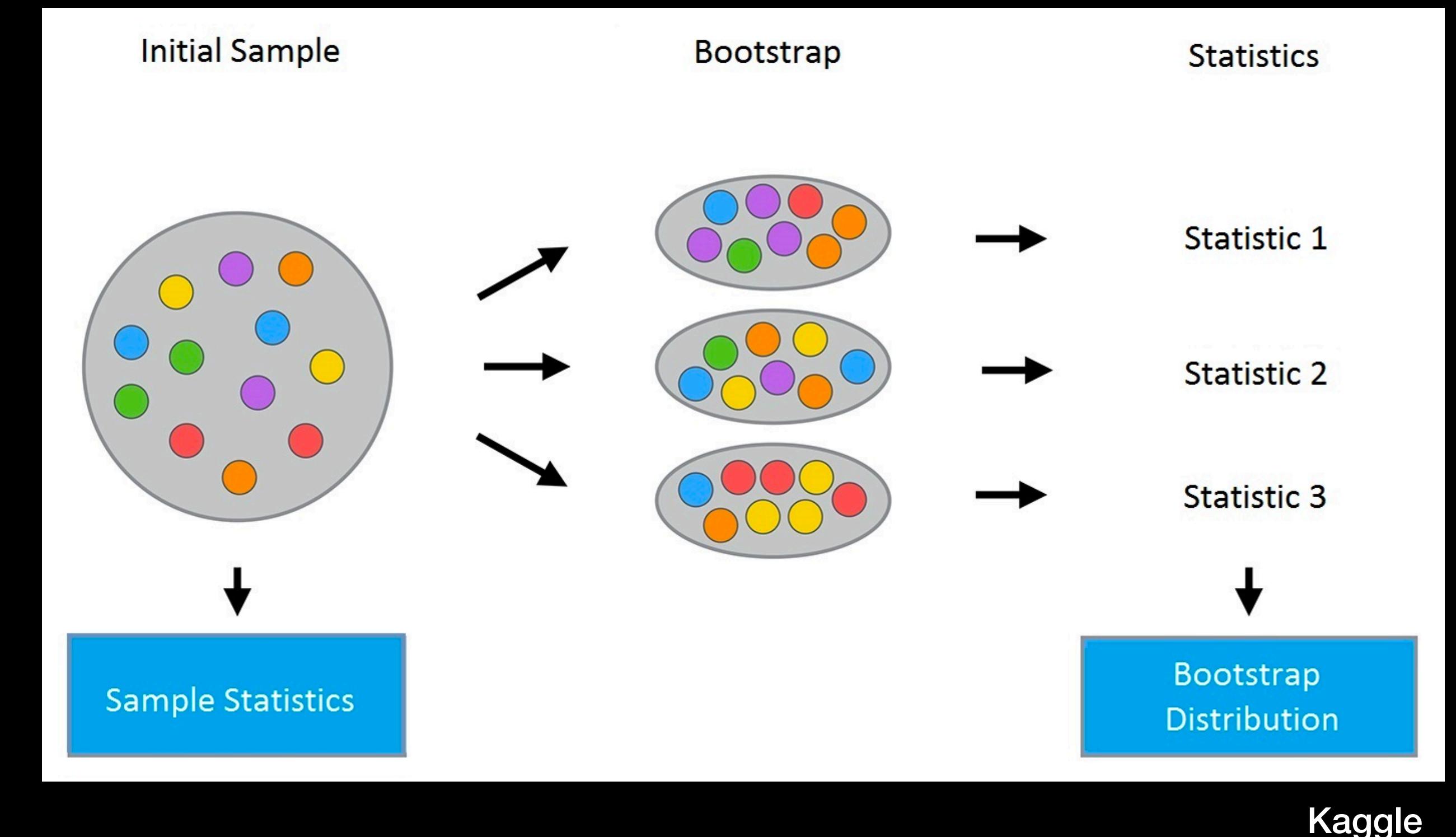


Cordes & Lazio 2002



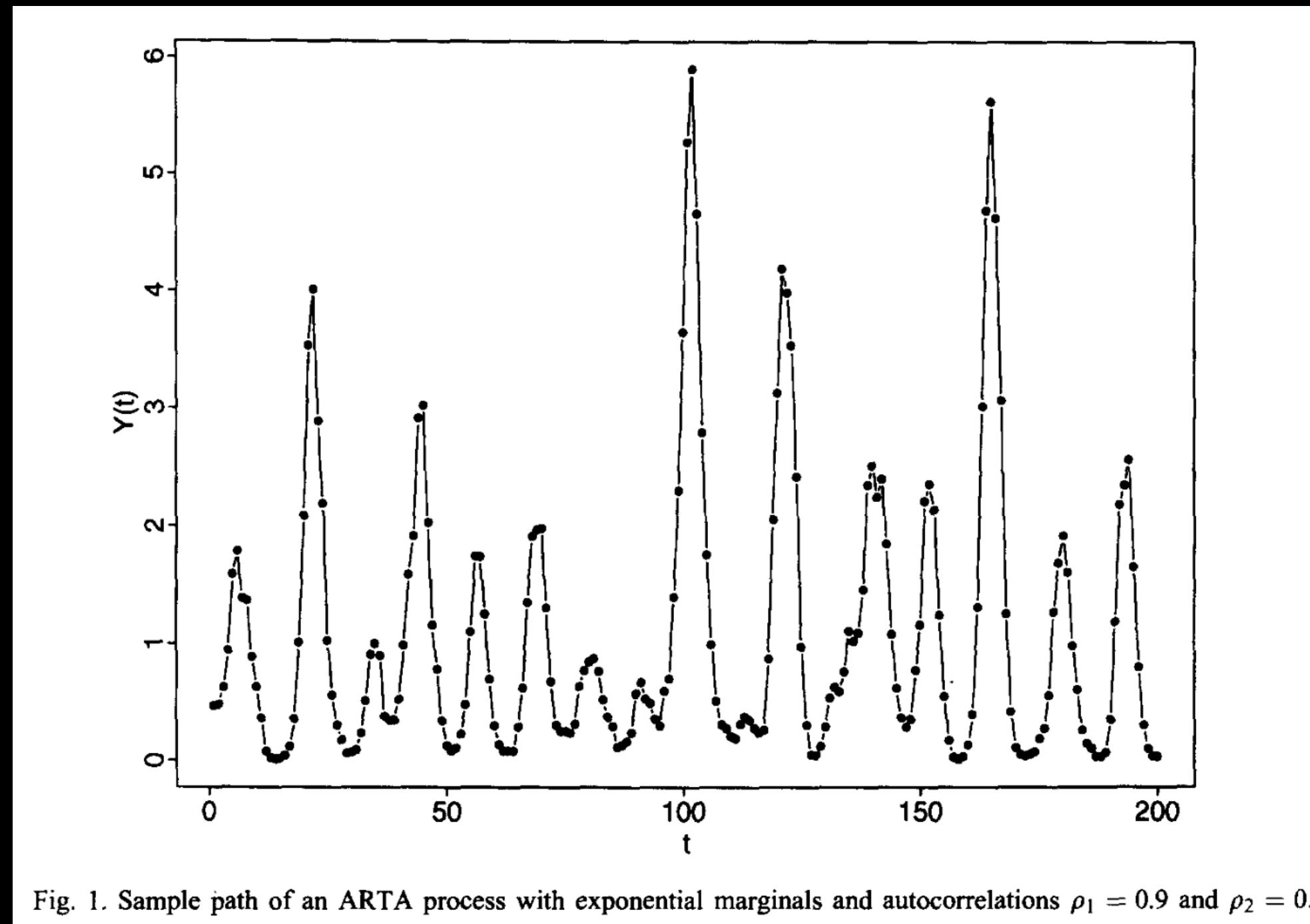
Low sample regime

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



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)



Cario & Nelson 1996

