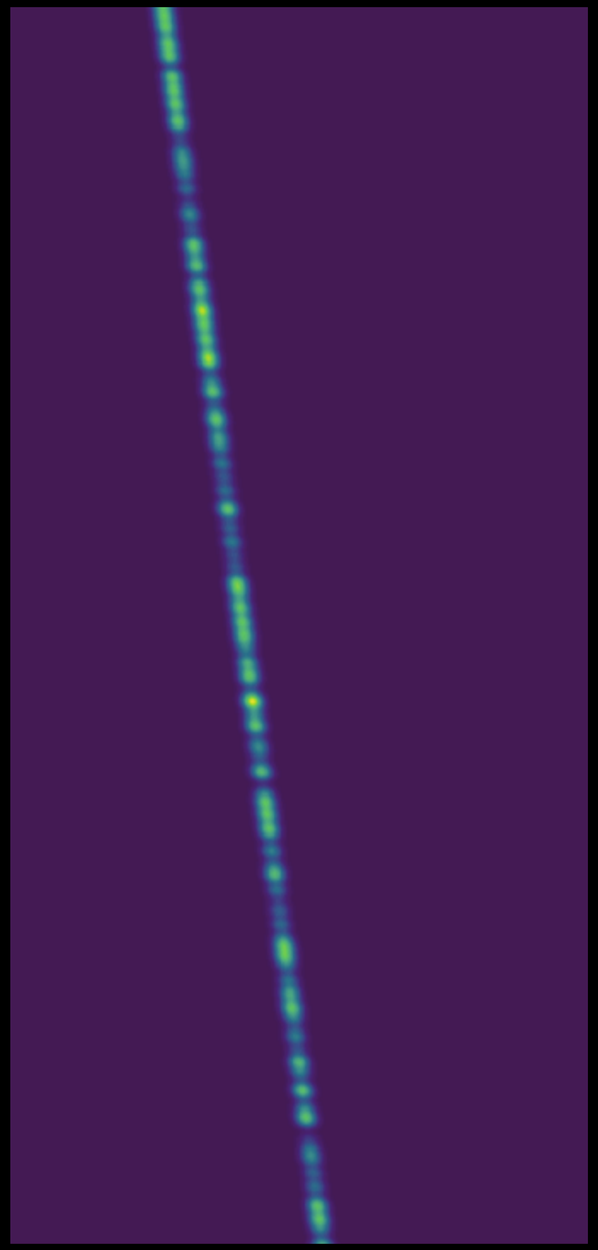


BREAKTHROUGH LISTEN

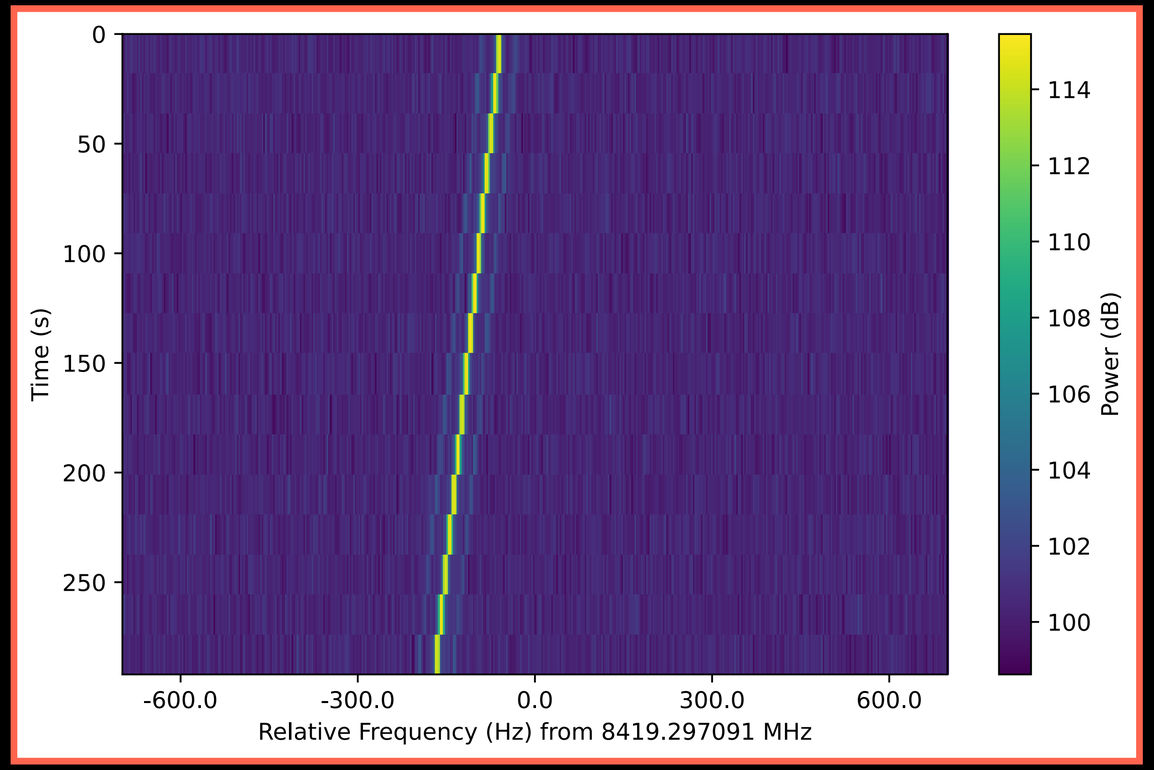
Algorithmic and Astrophysical Methods in the Search for Radio Technosignatures

Bryan Brzycki
University of California Berkeley
REU Seminar, July 3, 2024

BERKELEY SETI RESEARCH CENTER

Anatomy of a narrowband radio transmission

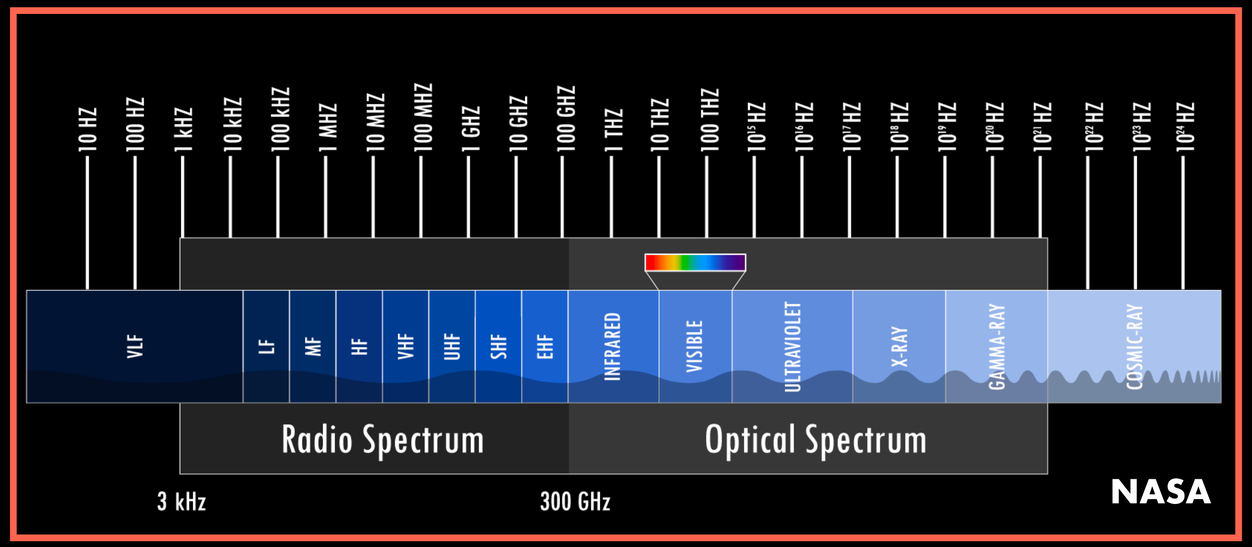
- Time-frequency spectrogram, or dynamic spectra
- High duty cycle, or continuous wave
- Doppler drift: changing Doppler shift from relative acceleration



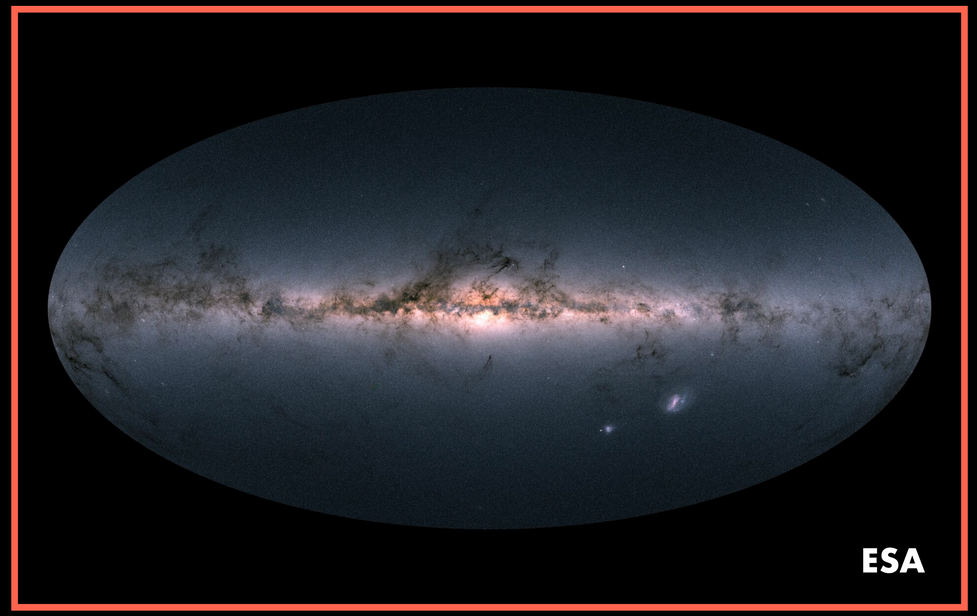
Detected signal from Voyager 1

Where should we look?

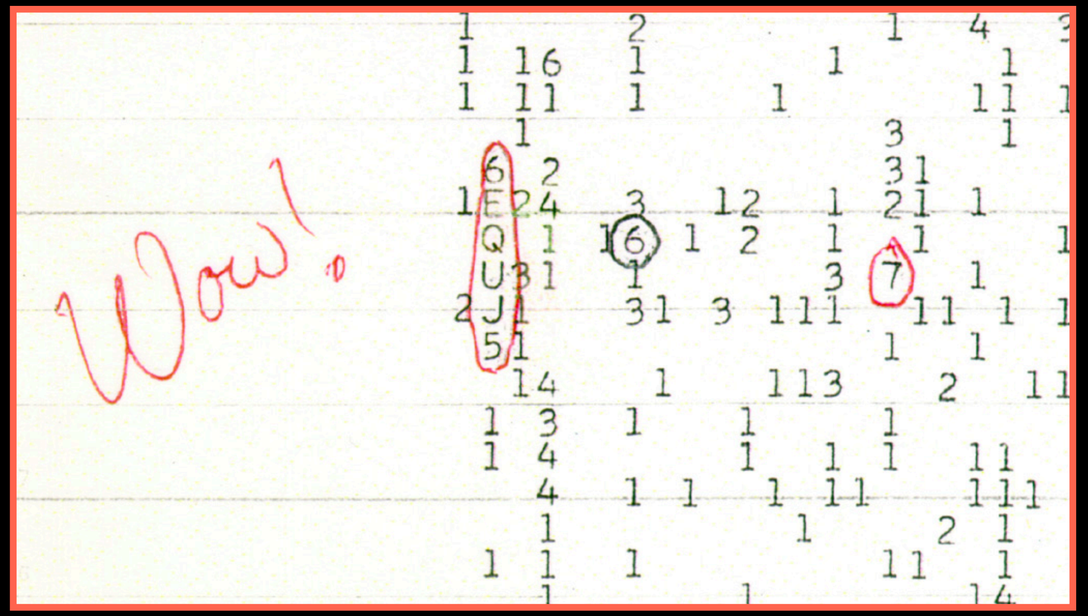
Frequency



Direction



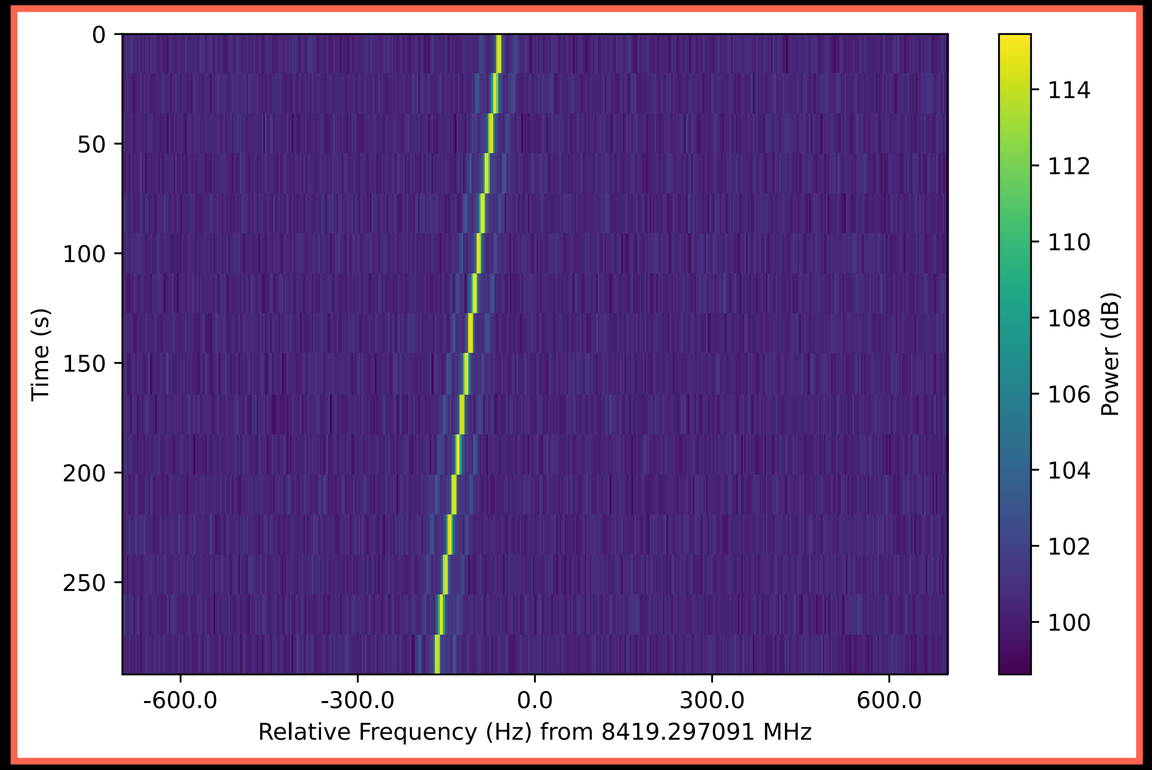
Time



Big Ear Radio

Modern radio SETI in practice

- Basic signal detection
    - Gather all signals possible above signal-to-noise threshold
- Candidate identification and differentiation
    - Primarily against human-created radio frequency interference (RFI)
    - Lots of manual inspection



Detected signal from Voyager 1

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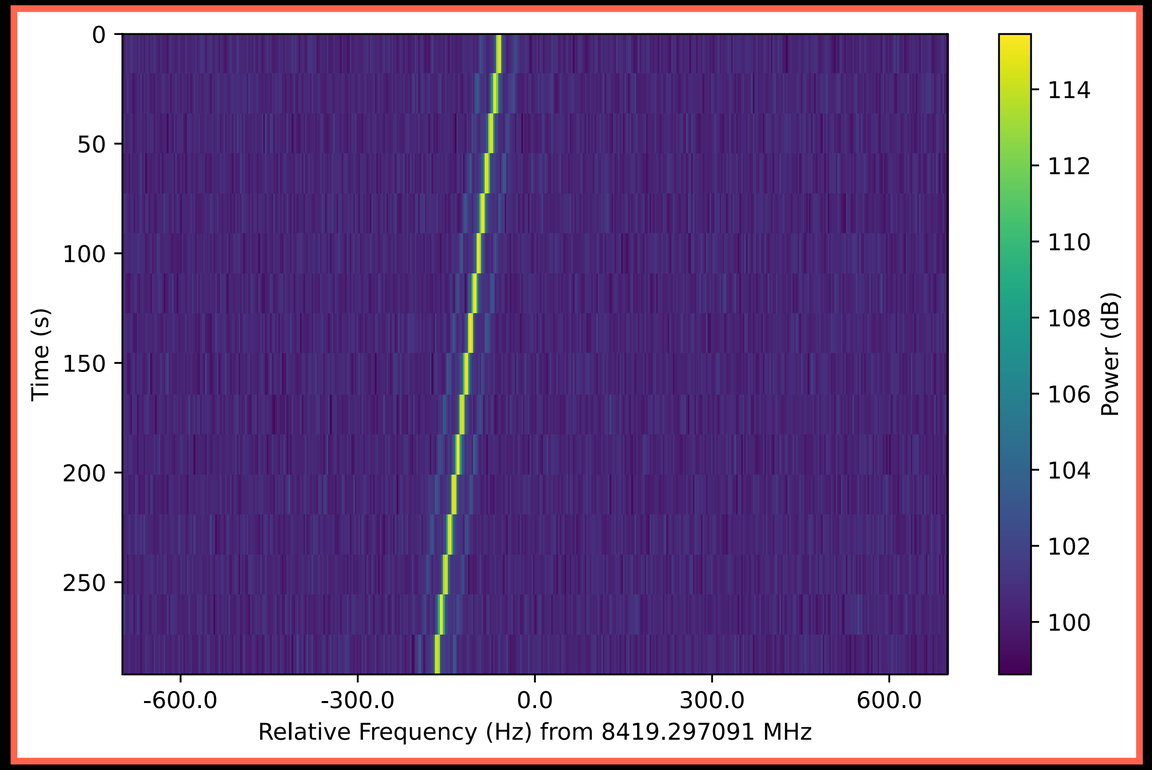
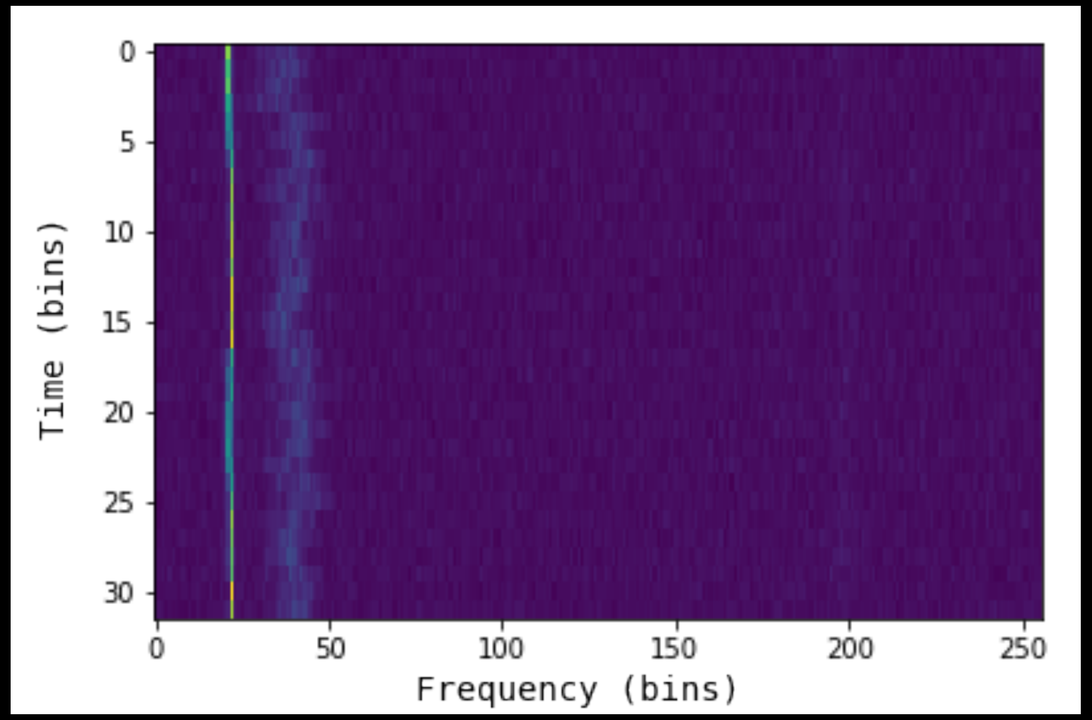


Detected signal from Voyager 1

Signal detection / localization with machine learning

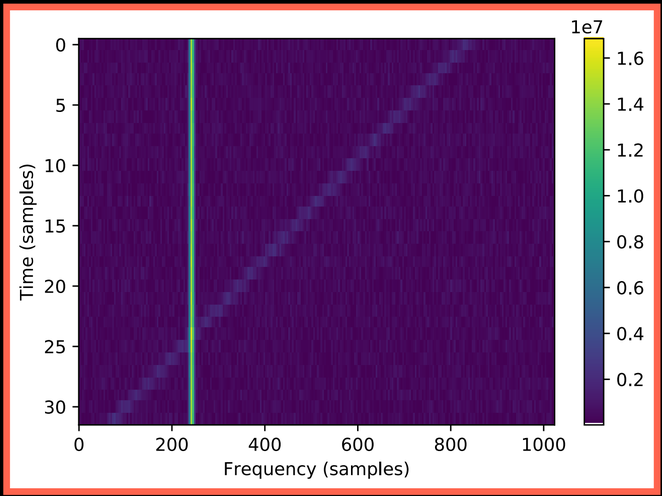
- Standard integration-based pipeline:
  - Dim signals concealed by nearby bright signals
  - Computationally expensive to search high drift rates



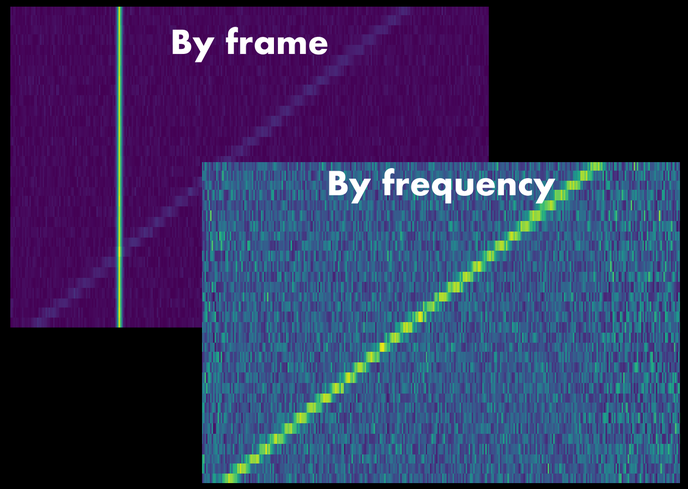
Snippet of GBT data at C-band

Brzycki et al. 2020, PASP

Synthetic training data

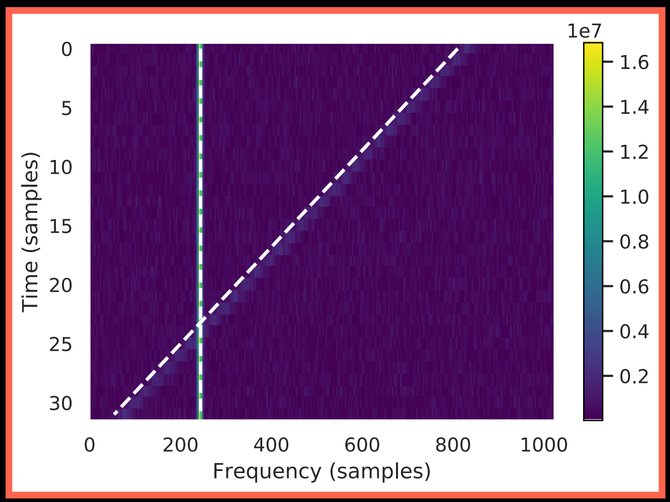


Normalization



Convolutional Neural Network

Predicted locations

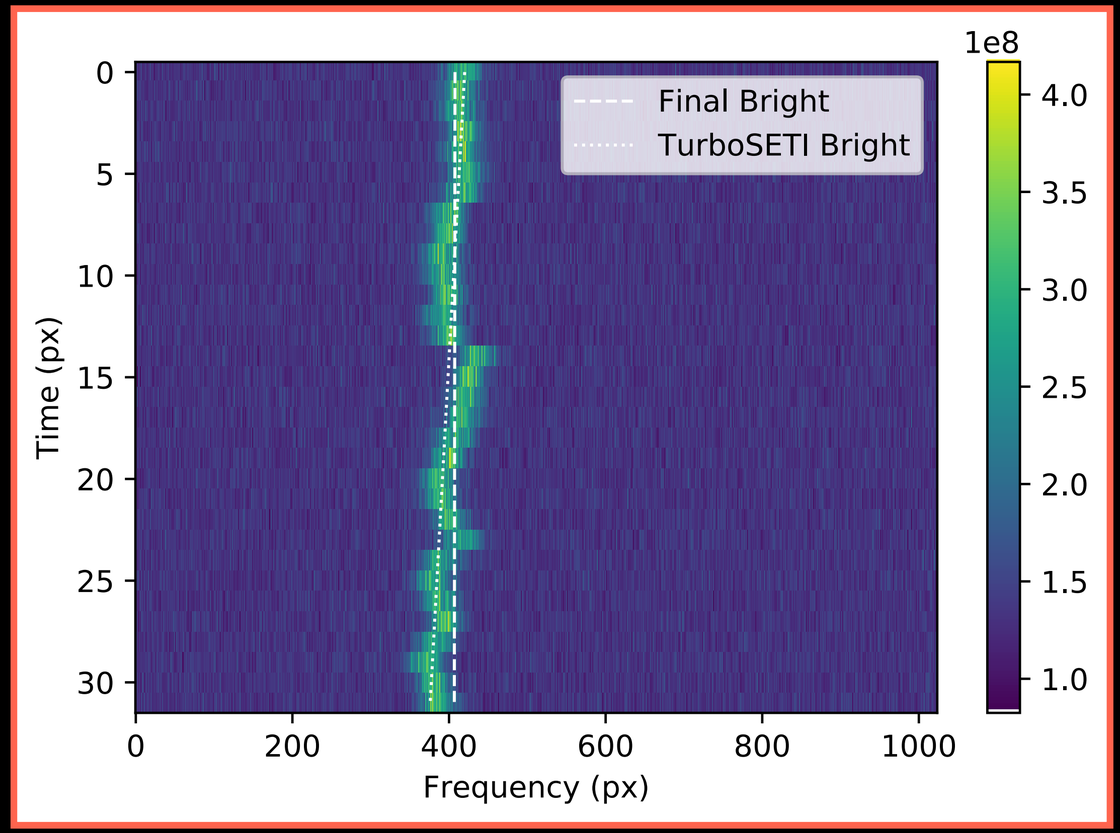


Brzycki et al. 2020, PASP

Takeaways

- Less accurate than deDoppler methods, but generally 20-40x faster

- Trained on ideal signals but still relatively robust

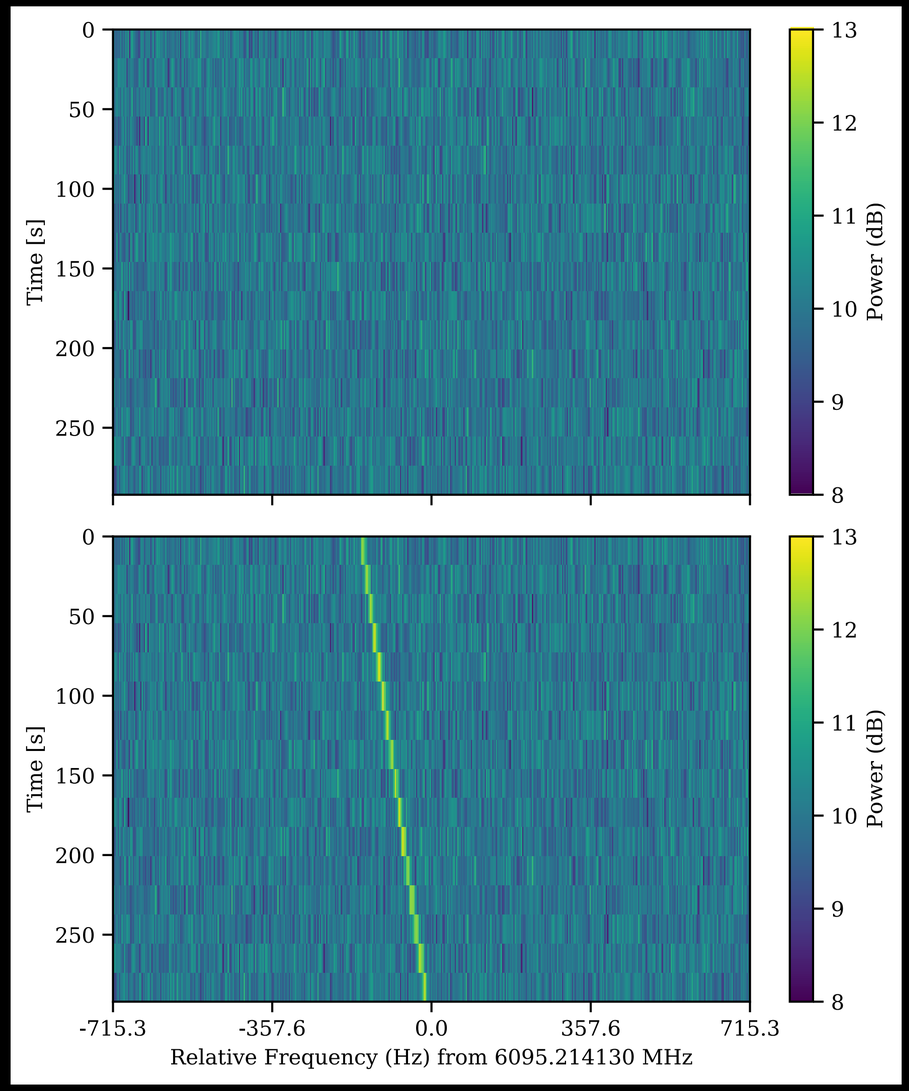


C-band RFI signal, with ML prediction dashed and TurboSETI localization dotted.

Brzycki et al. 2020, PASP

Setigen

- Open-source Python library for creating 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 ☆ 25 12

Brzycki et al. 2022, AJ

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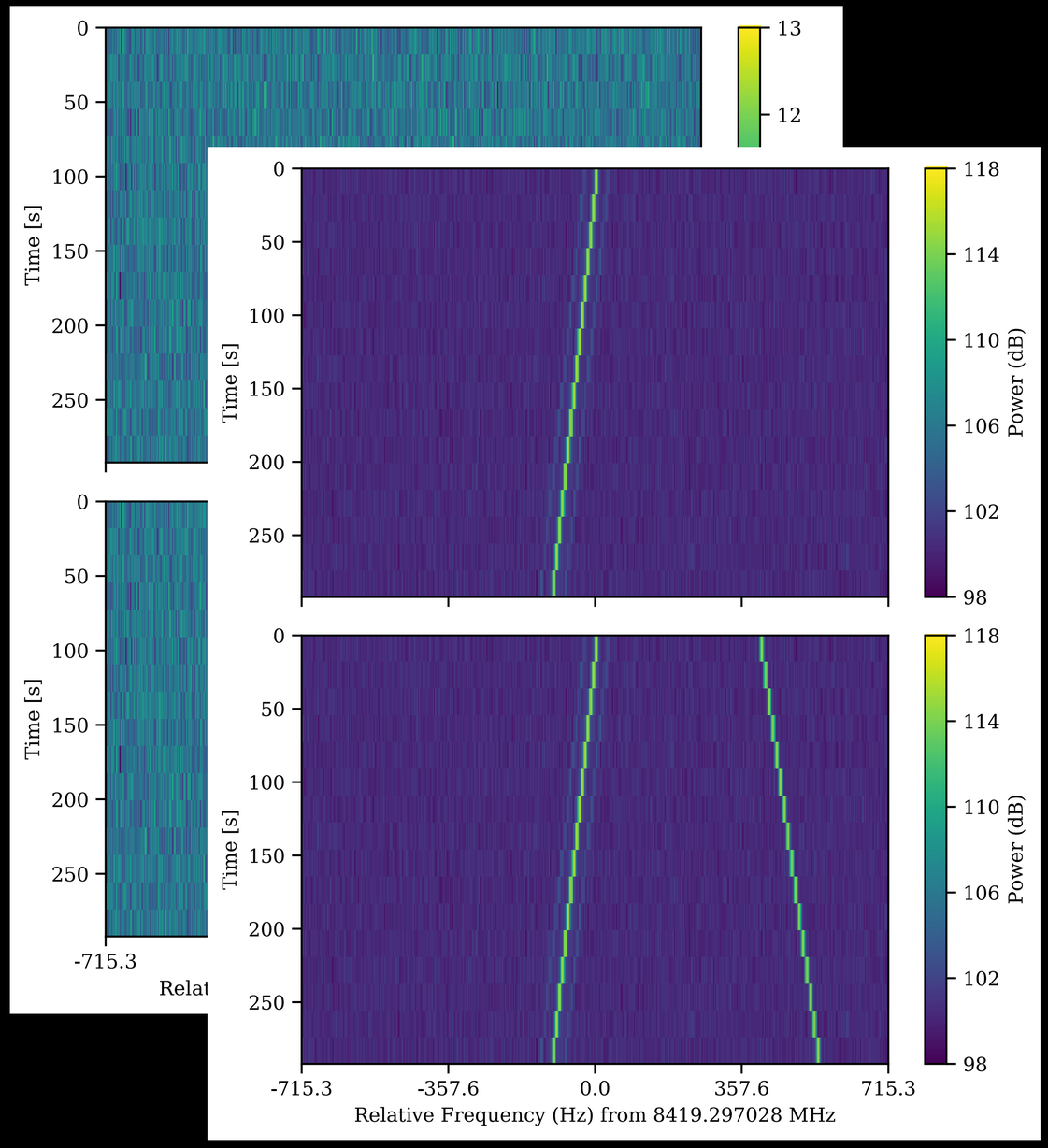
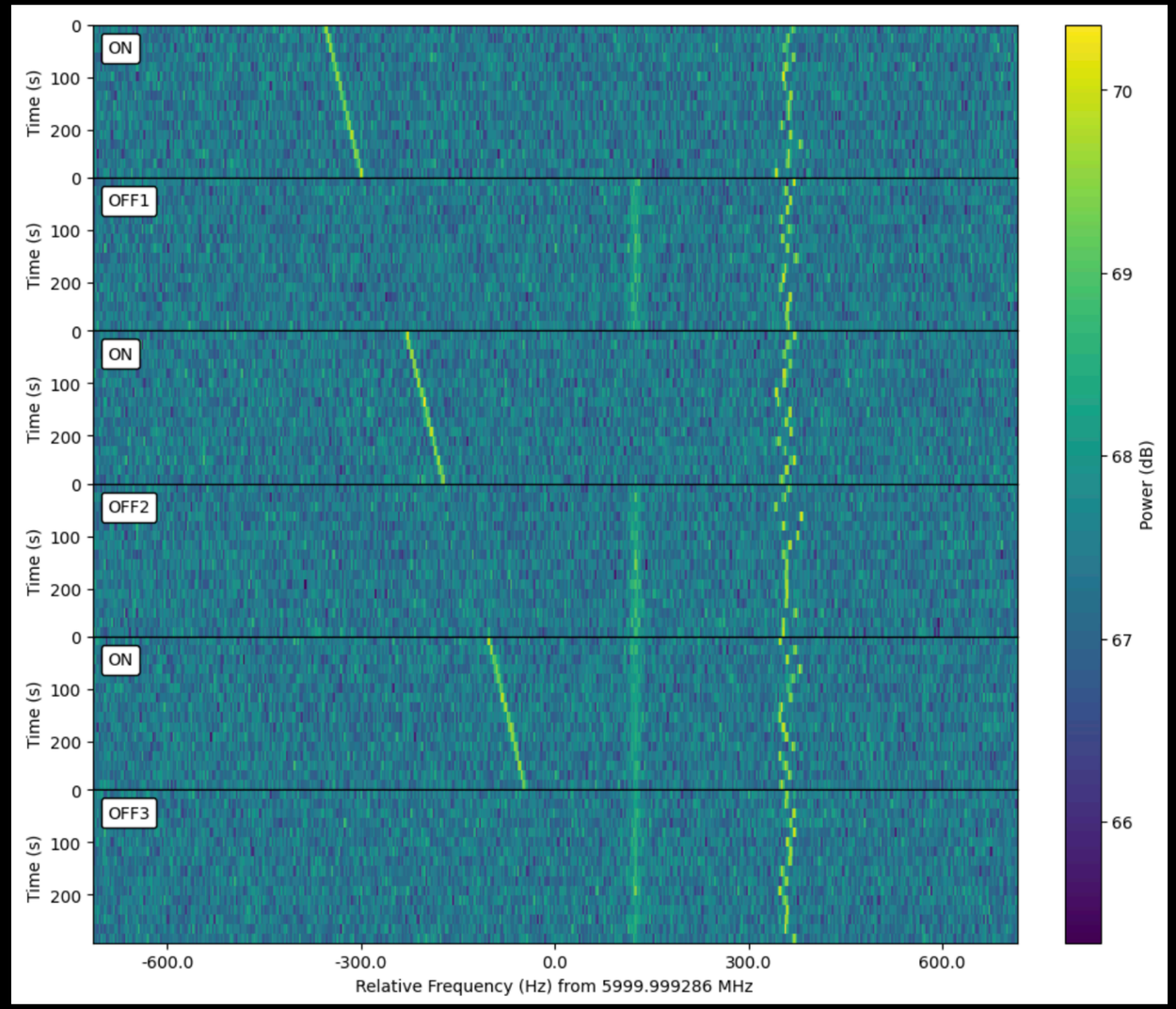
Jupyter Notebook ☆ 25 12



Brzycki et al. 2022, AJ

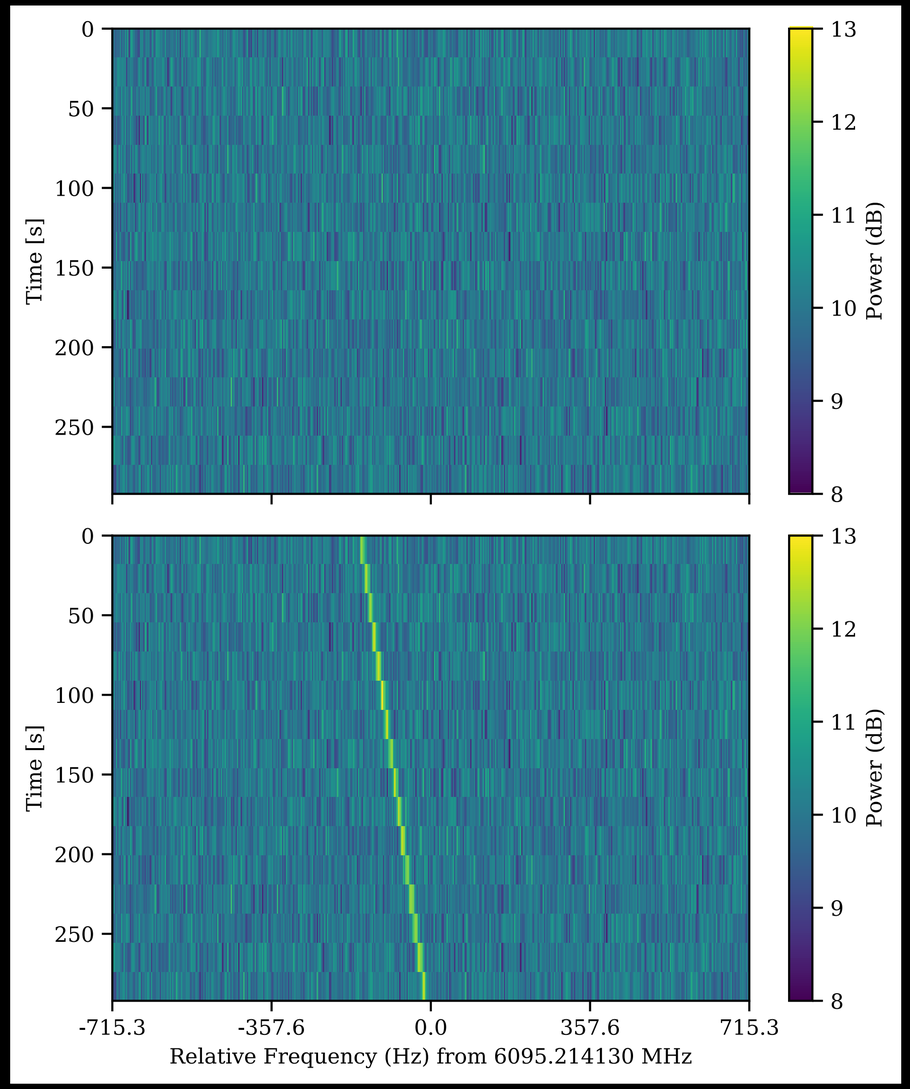
Setigen

- Open-source = always something to contribute and improve!
- Project has expanded massively since inception:
    - Support for full observational cadences
    - Publication-ready figures
    - More advanced operations such as deDrifting, slicing, and integration-based Doppler-smearing
    - Voltage synthesis and basic frontend simulation (.raw complex voltages)



Setigen's basic design philosophy

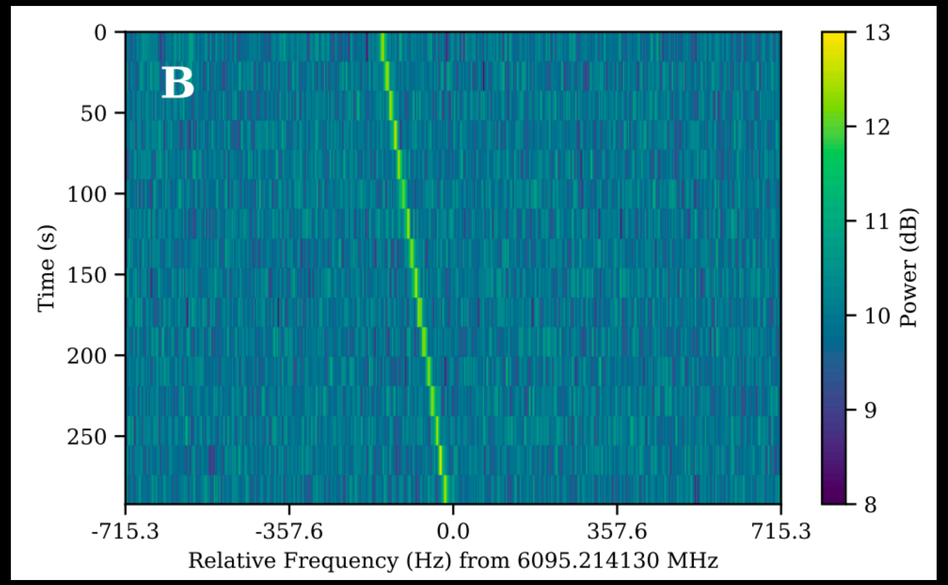
- The Frame class is used to represent a basic time-frequency intensity spectrogram
- Can load in .fil or .h5 data directly into Frames, or generate synthetic chi-squared noise
- Signal injection methods adds power on top of existing Stokes I data — this is not technically "correct"!
    - (x^2 + y^2) vs. (x + y)^2



Setigen's basic spectrogram signal calculation

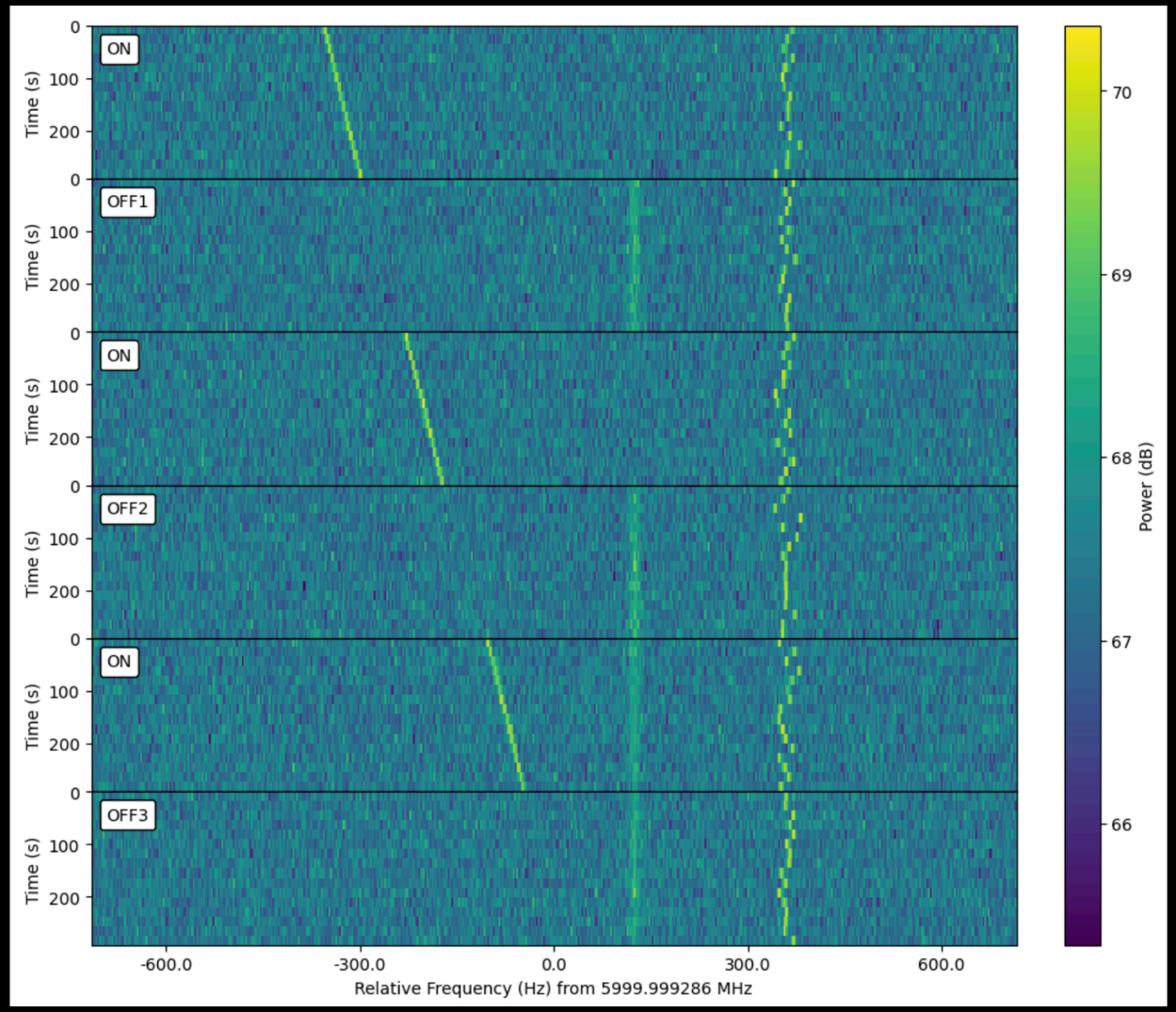
1. `path`—$I_p(t)$: Central signal frequencies as a function of time, e.g., linear (constant) drift rate, quadratic drift rate
2. `t_profile`—$I_t(t)$: Signal intensity as a function of time, e.g., constant intensity, Gaussian pulses
3. `f_profile`—$I_f(f, f_0)$: Spectral profile as a function of frequency (offset from central frequency), e.g., sinc^2 profile, Gaussian profile
4. `bp_profile`—$I_{bp}(f)$: Bandpass profile as a function of absolute frequency

$$I(t, f) = I_t(t) I_f(f, I_p(t)) I_{bp}(f).$$

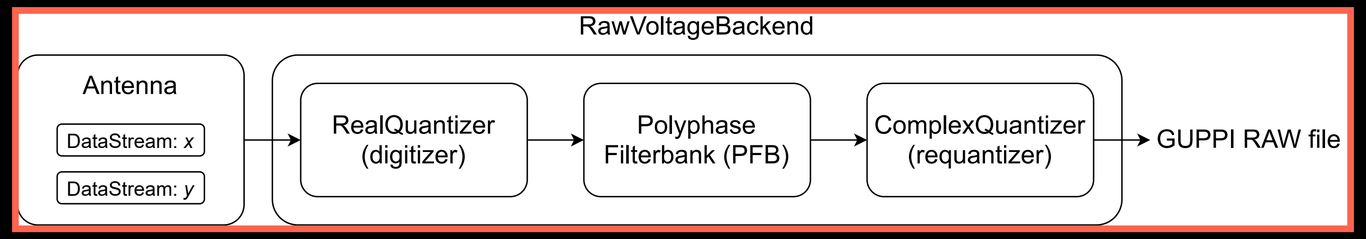


Setigen's basic design philosophy

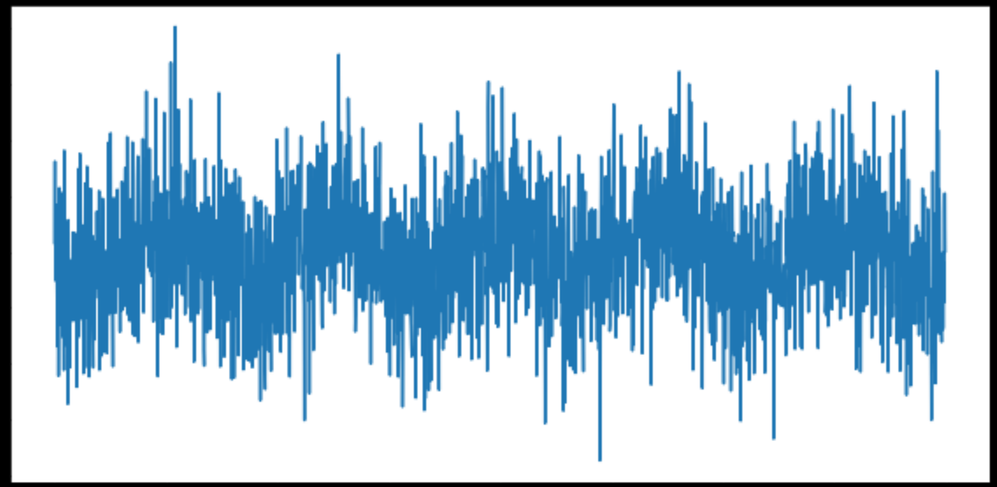
- The Cadence object can be thought of as a souped-up array of Frames
- Can use array slicing, like in NumPy, to select which Frames to inject signals
- Can specify the cadence type, e.g. ABACAD, and filter by letter
- Mainly convenience so you don't need to manually track relative time for signal calculations



Setigen's voltage module design philosophy



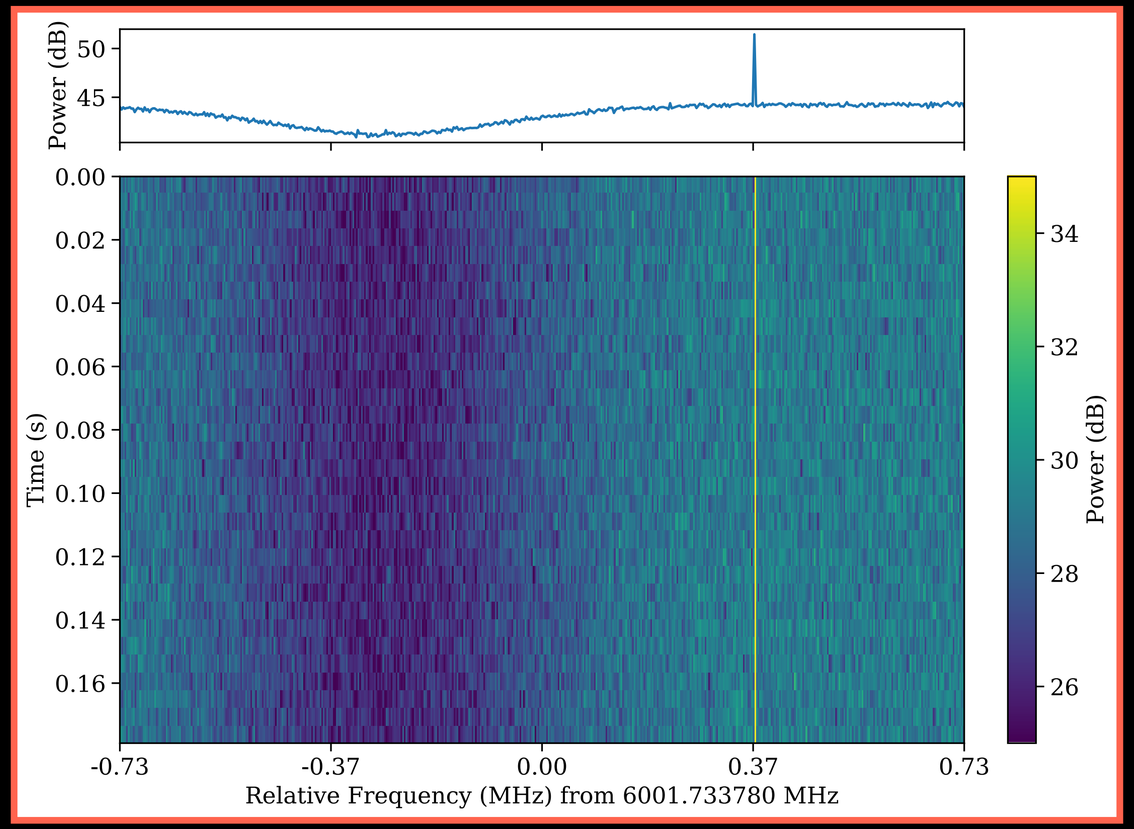
- Synthetic complex voltage data
- Noise and signal injection is done at the real voltage level, as an antenna would receive power – you would put a sine wave for a perfect non-drifting monotone signal
- Simple (but effective) models of real pipeline components, such as digitizers and a polyphase filterbank



Brzycki et al. 2022, AJ

Setigen's voltage module design philosophy

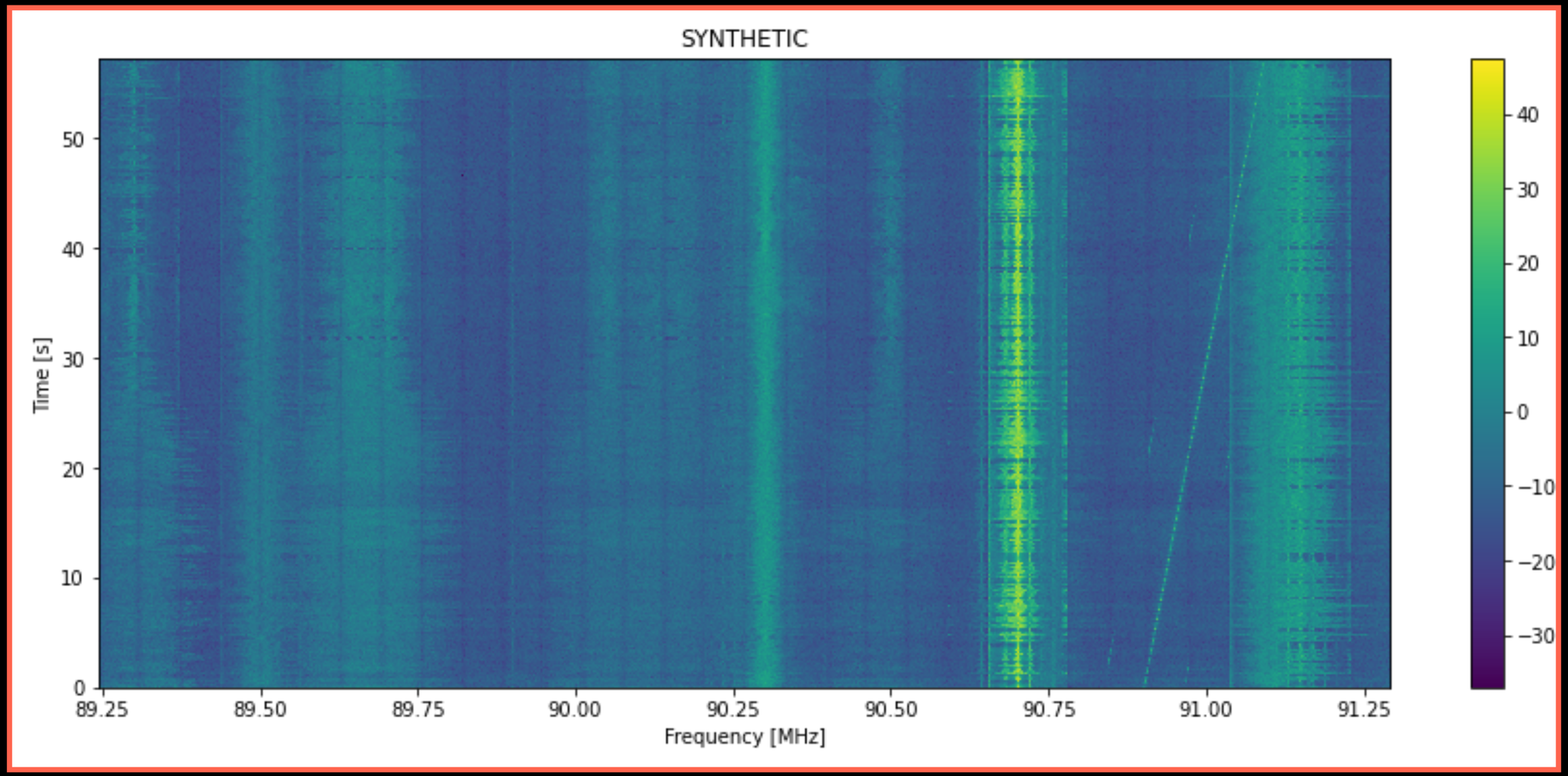
- Data formats and steps are based on Breakthrough Listen conventions, e.g. GUPPI RAW format
    - Used to test end-to-end detection pipeline (reduction, etc.)
- Wayyy more expensive compared to spectrogram injection, but is the most "correct" way to do things. Can use GPU to accelerate, which helps a bit.



Brzycki et al. 2022, AJ

Silly RTL-SDR demo injection

github.com/bbrzycki/rtlsdr-to-setigen

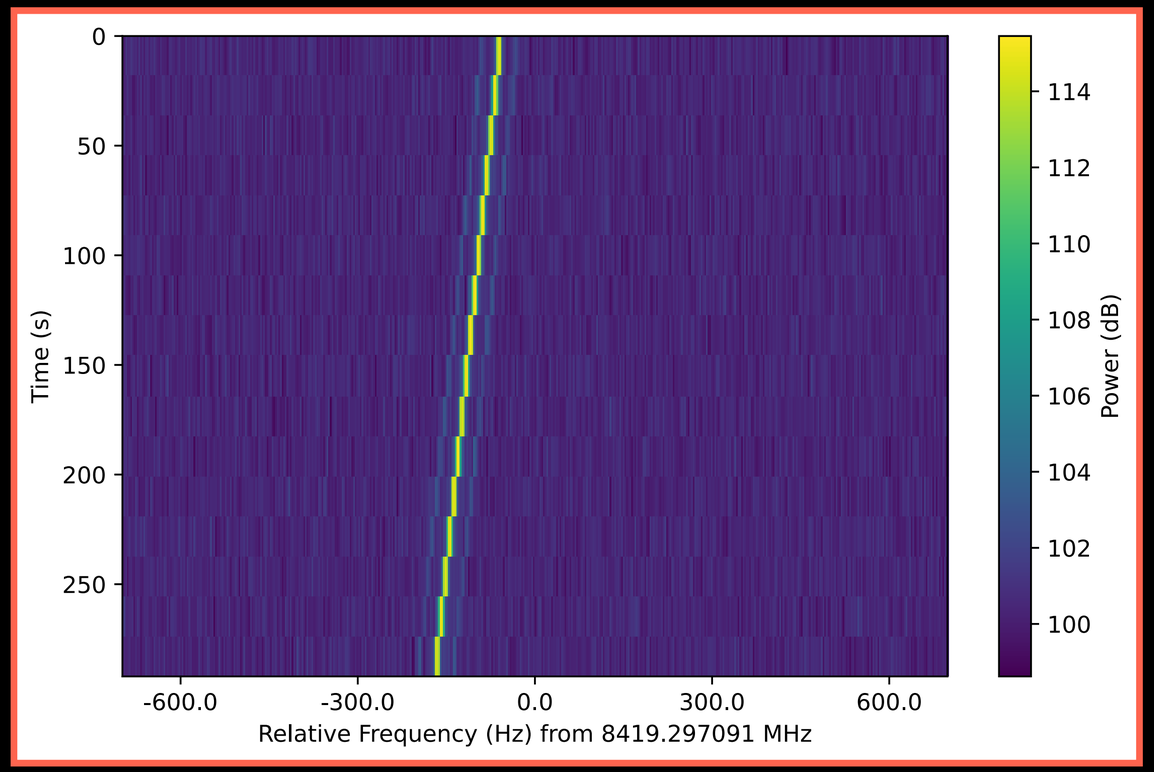


Links, if any of this sounds helpful for your project!

- github.com/bbrzycki/setigen
- setigen.readthedocs.io
- Brzycki et al. 2022, AJ
    - In particular, includes a discussion of the essential single-dish signal chain with some useful equations

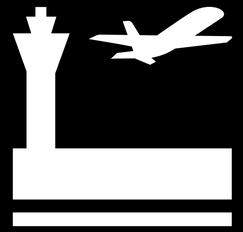
Modern radio SETI in practice

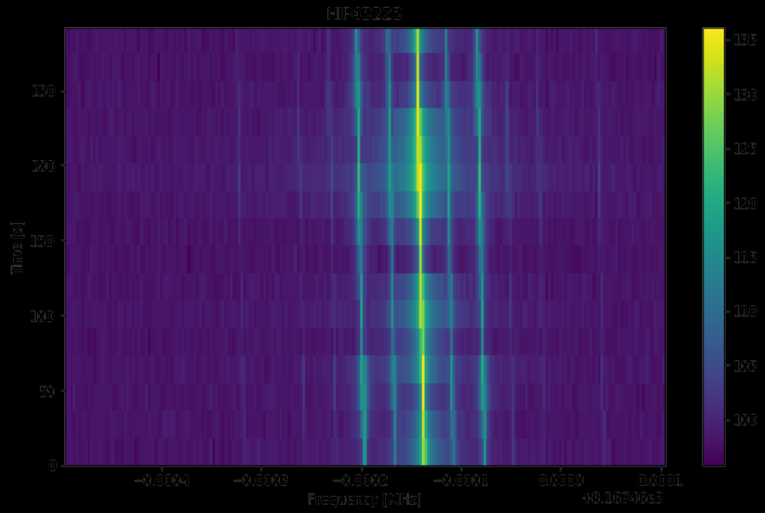
- Basic signal detection
  - Gather all signals possible above signal-to-noise threshold
- Candidate identification and differentiation
  - Primarily against human-created radio frequency interference (RFI)
  - Lots of manual inspection

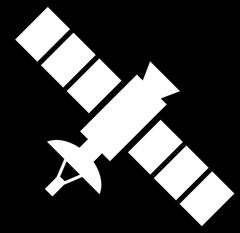


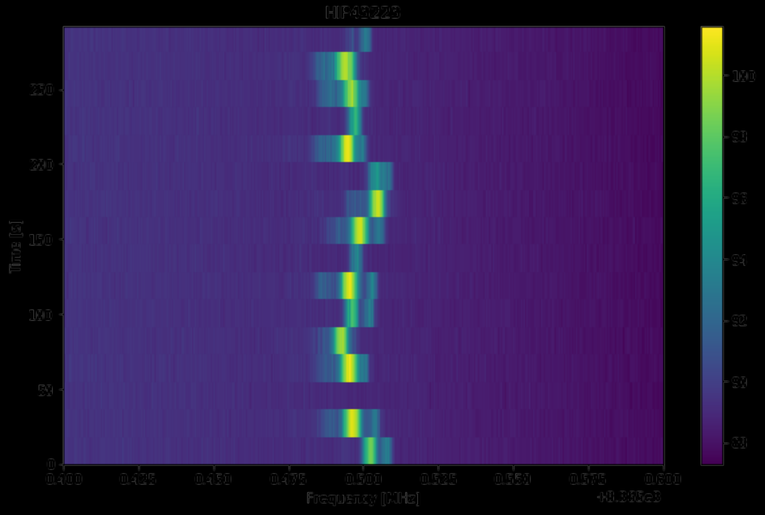
Detected signal from Voyager 1

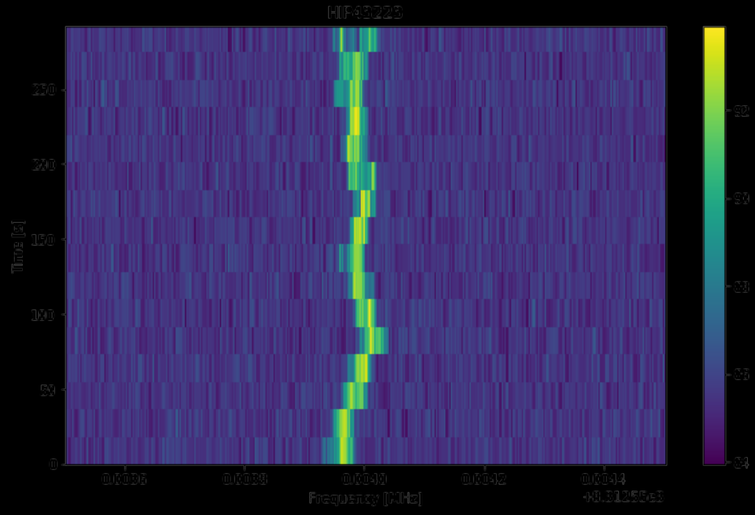
Differentiation against RFI

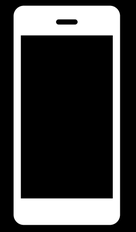




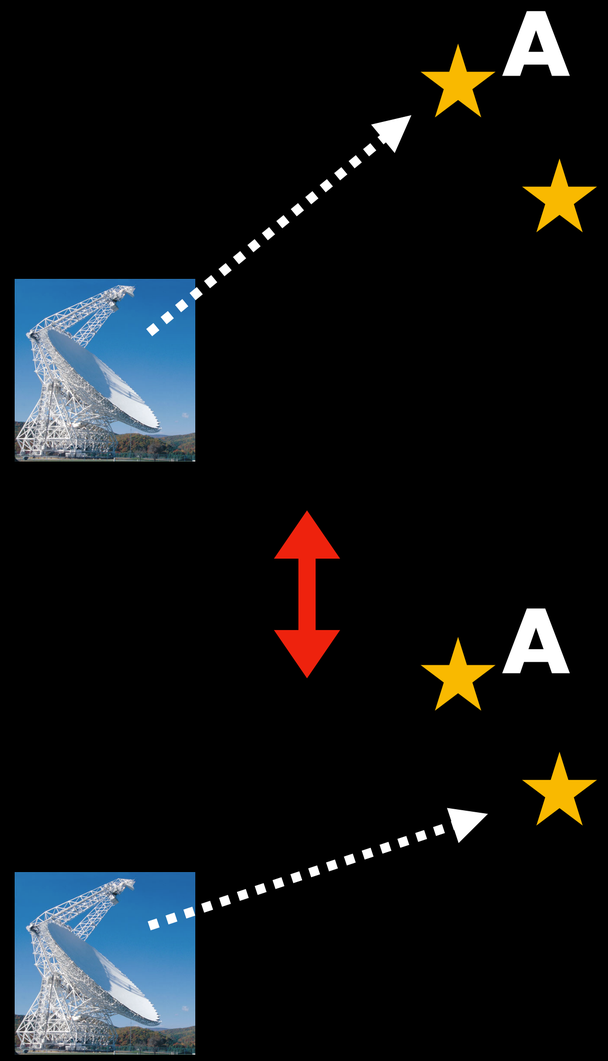




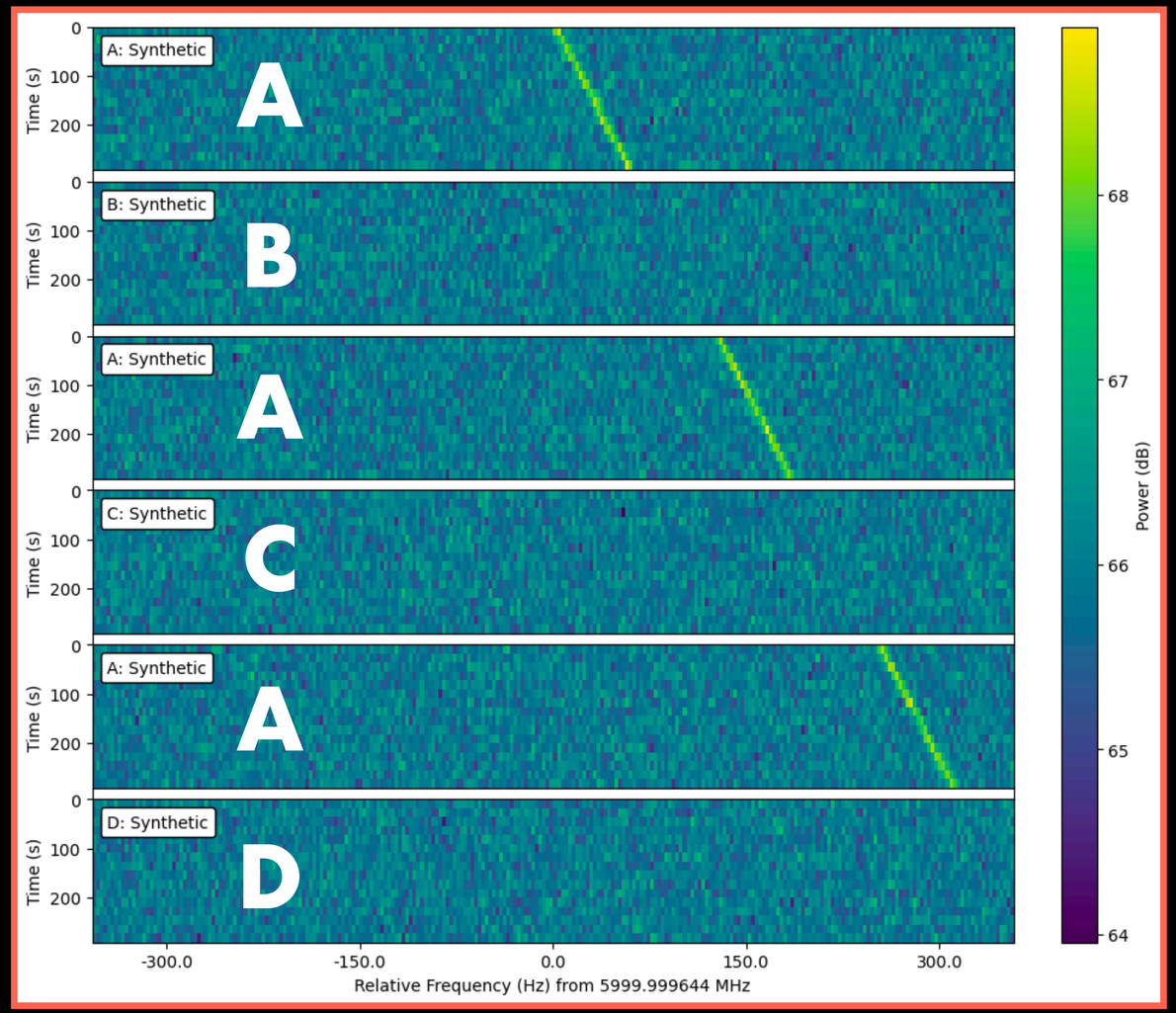




Sky localization (ON-OFF) filter



Time

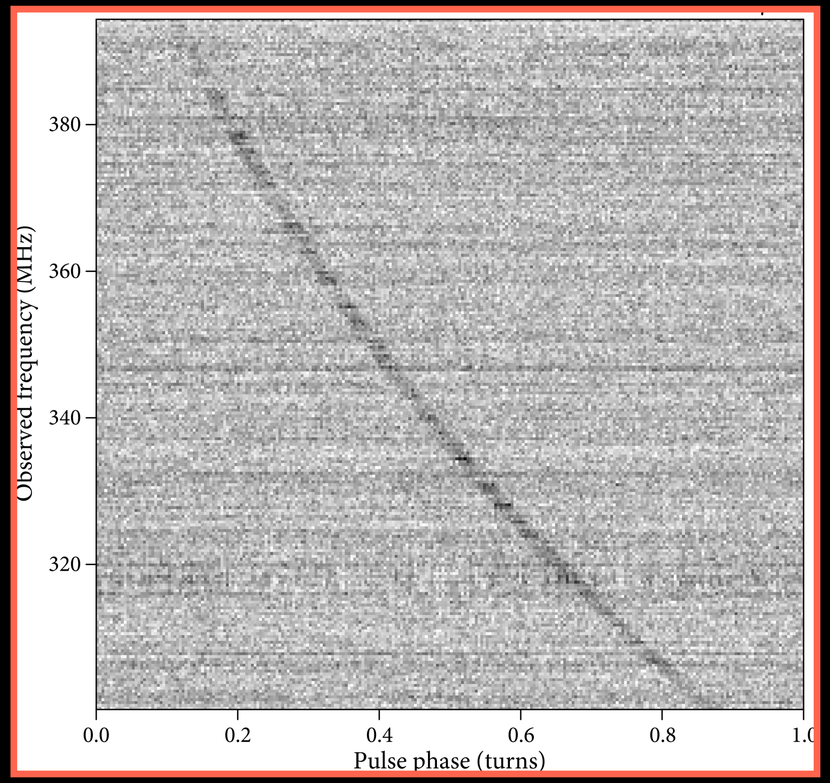


Frequency

Can we use astrophysical phenomena to distinguish technosignatures from RFI?

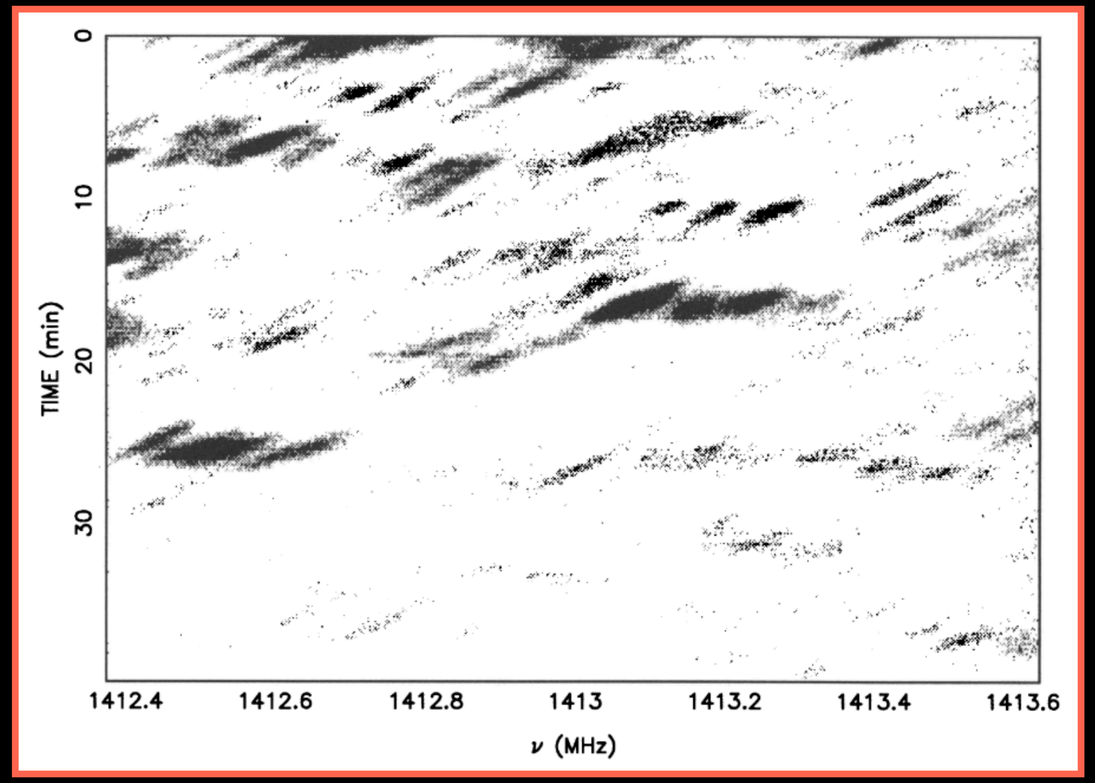
Pulsar observations probe radio ISM plasma effects

Dispersion



Condon & Ransom 2016

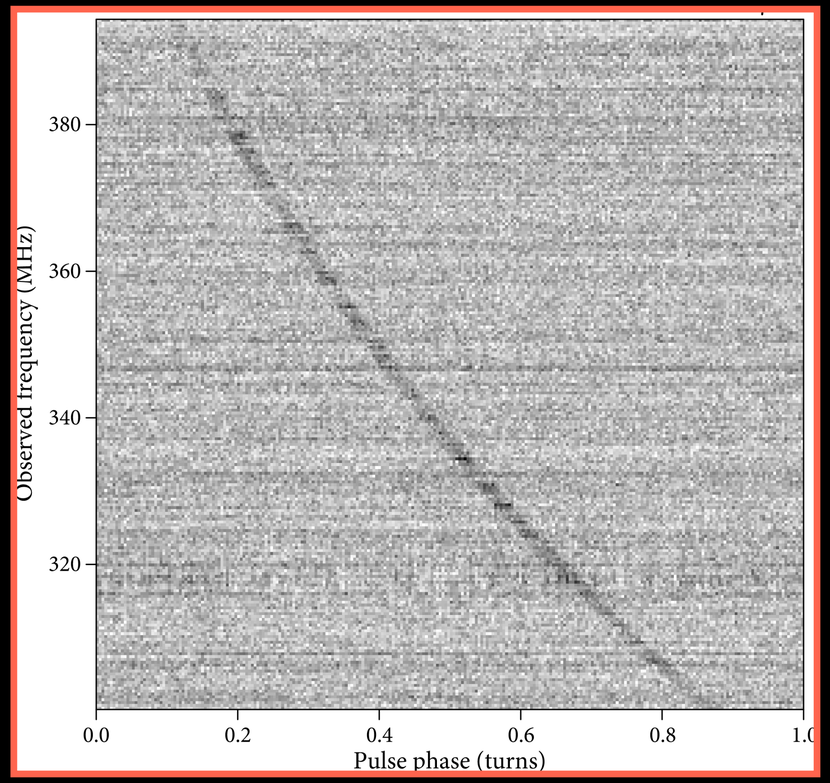
Scattering



Cordes & Lazio 1991

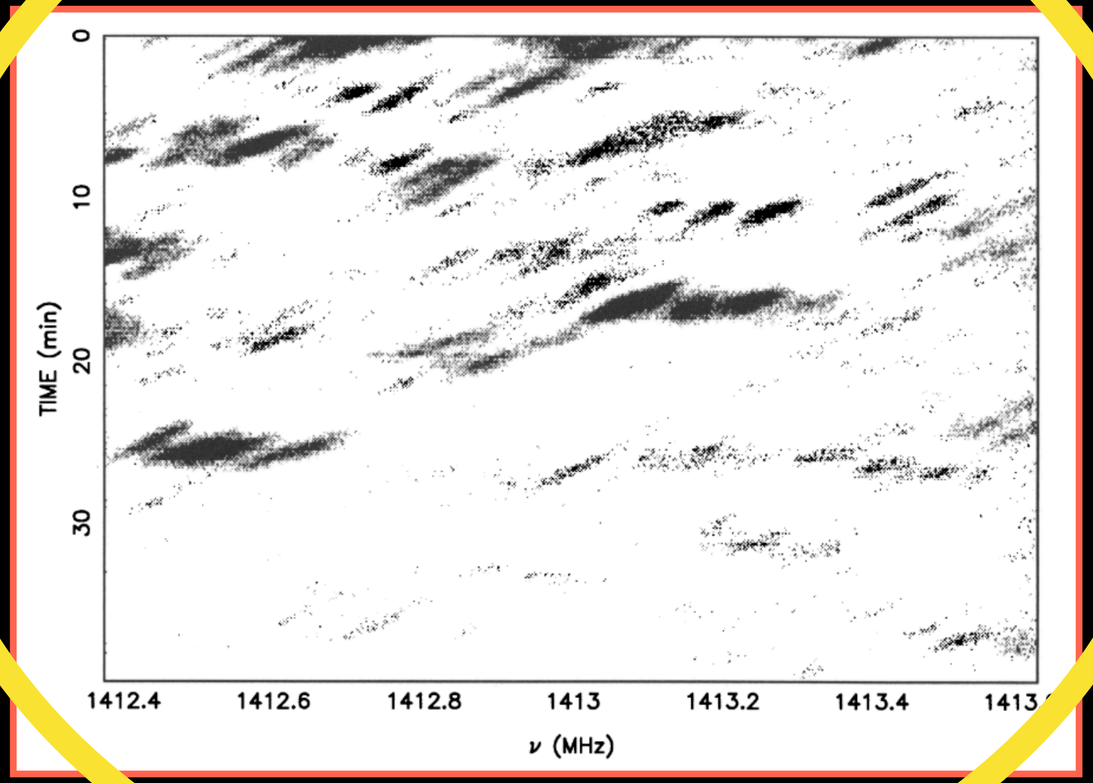
Pulsar observations probe radio ISM plasma effects

Dispersion



Condon & Ransom 2016

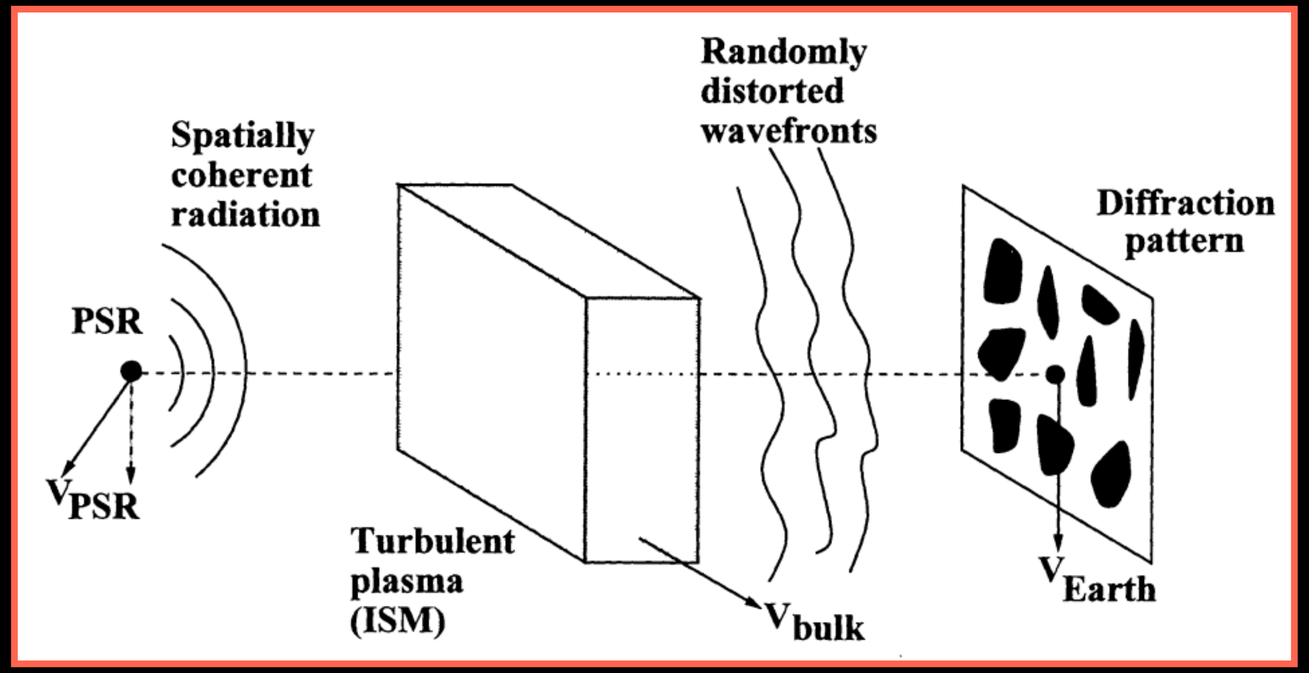
Scattering



Cordes & Lazio 1991

Diffractive scintillation in the ISM

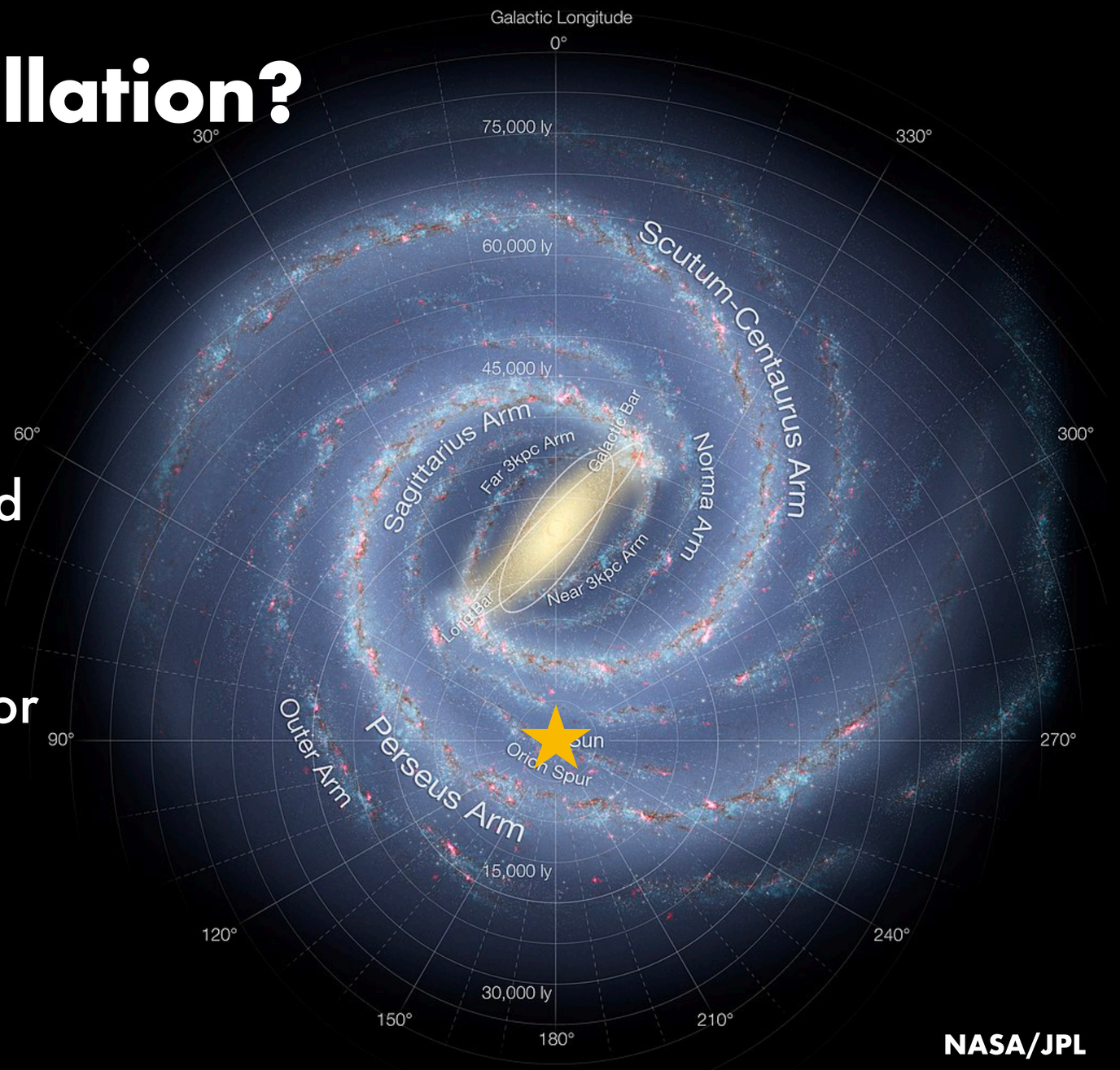
- Electron density fluctuations in ionized plasma → interference pattern
- Can lead to 100% intensity modulation, especially towards the Galactic center, with characteristic scintillation timescale Δt_d



Cordes 2002

Why search for 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



NASA/JPL

Can we detect scintillated narrowband technosignatures?

1. Given a signal exhibiting scintillations, can we identify it as such?
2. Can we differentiate scintillated signals from existing RFI (in terms of intensity modulation)?

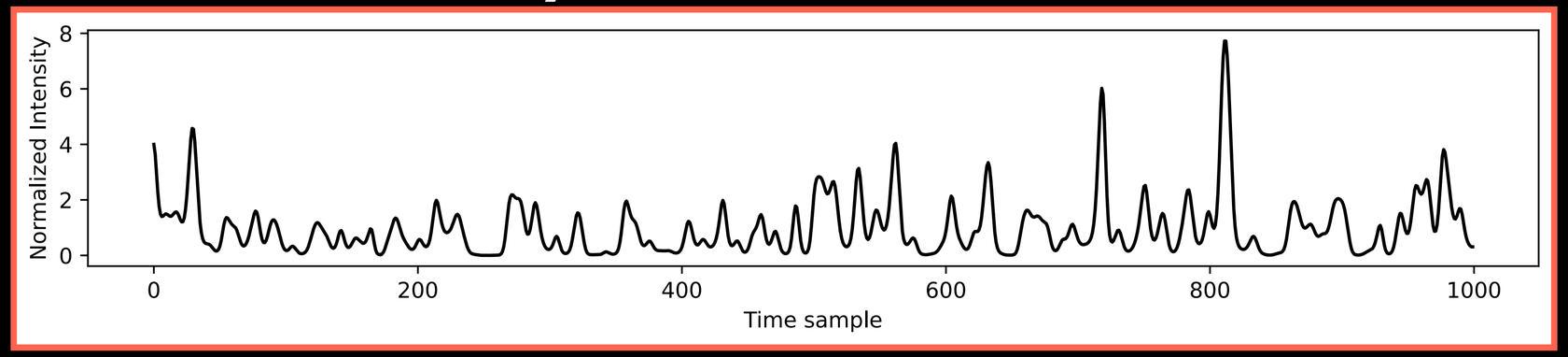
Brzycki et al. 2023, ApJ → Brzycki et al. (in prep)

What would strongly scintillated signals look like?

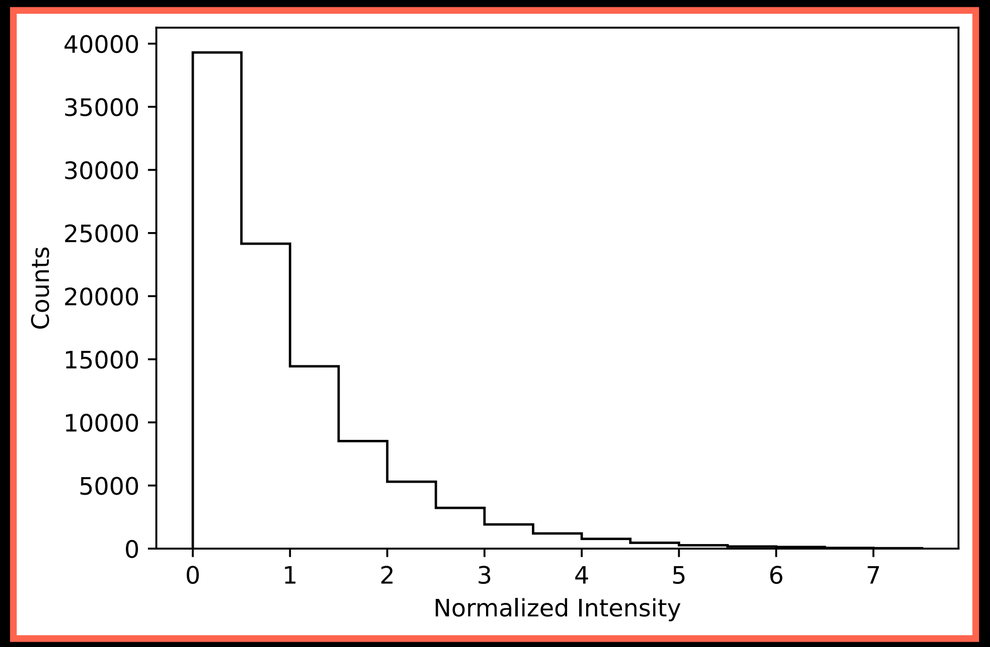
Cordes & Lazio 1991

Cordes, Lazio, & Sagan 1997

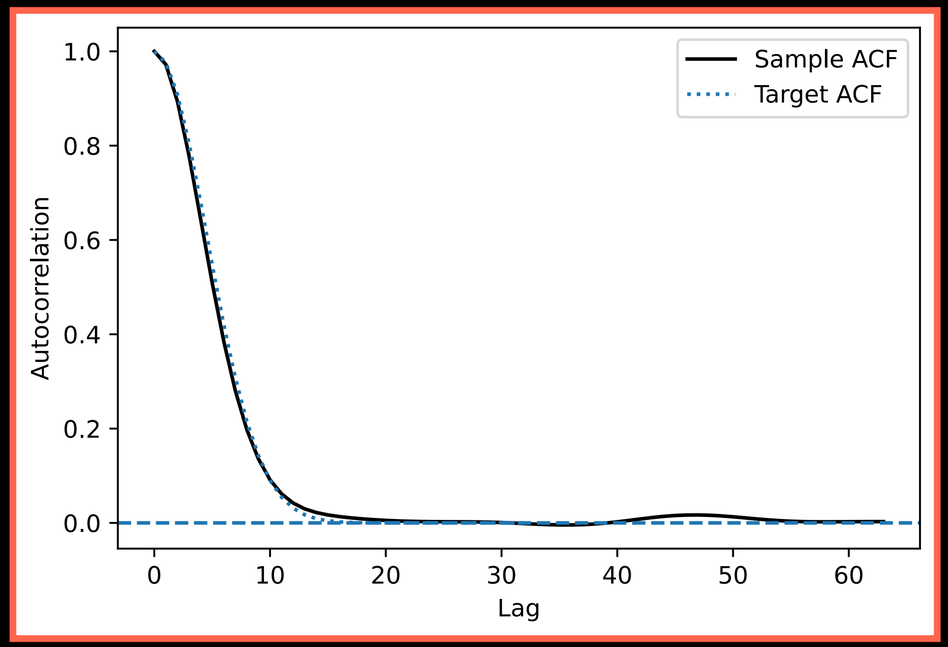
Synthetic time series



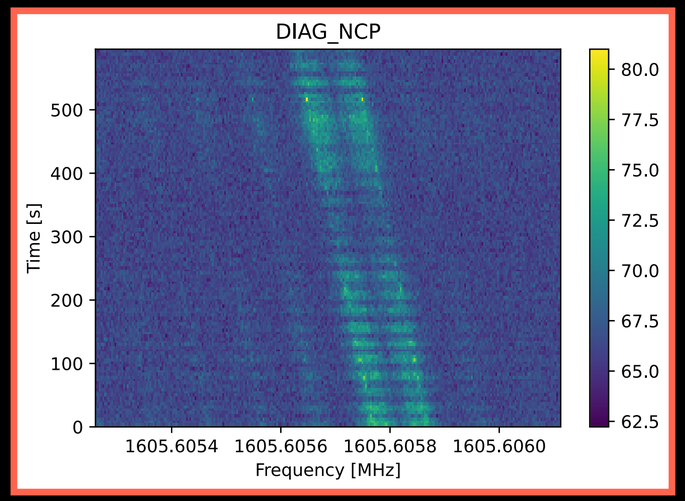
Exponential intensity distribution



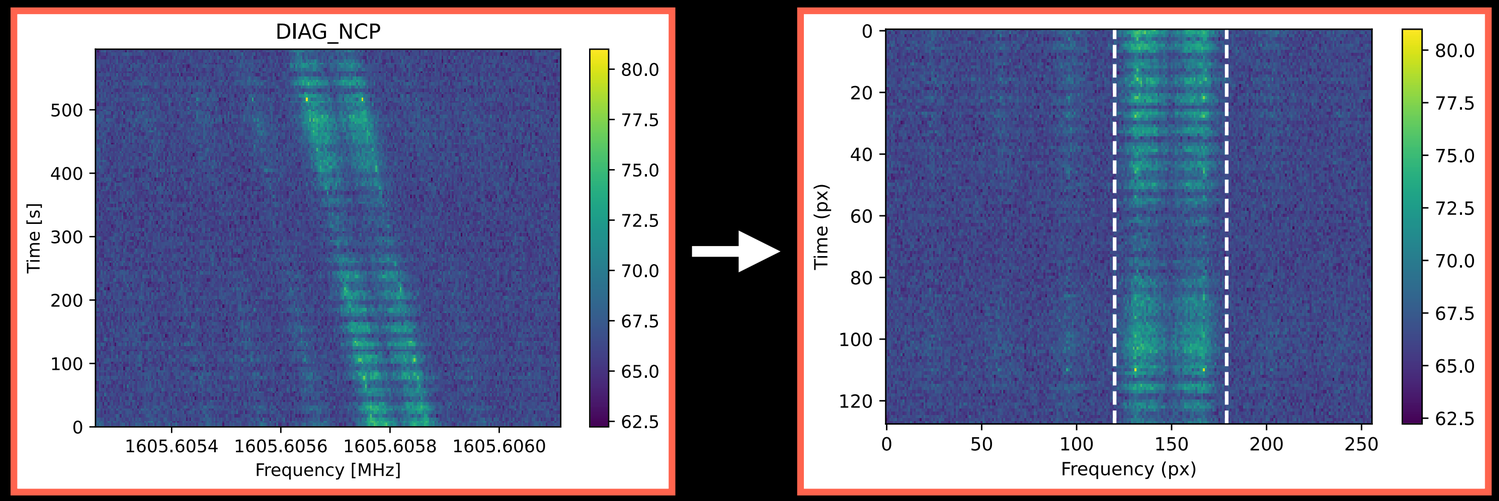
Near-Gaussian autocorrelation



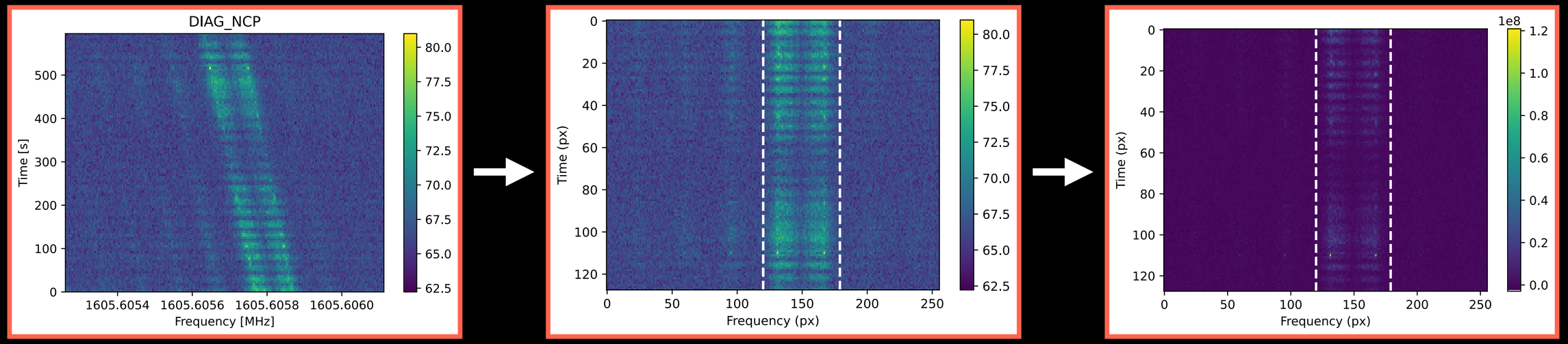
Analysis steps for a detected narrowband signal



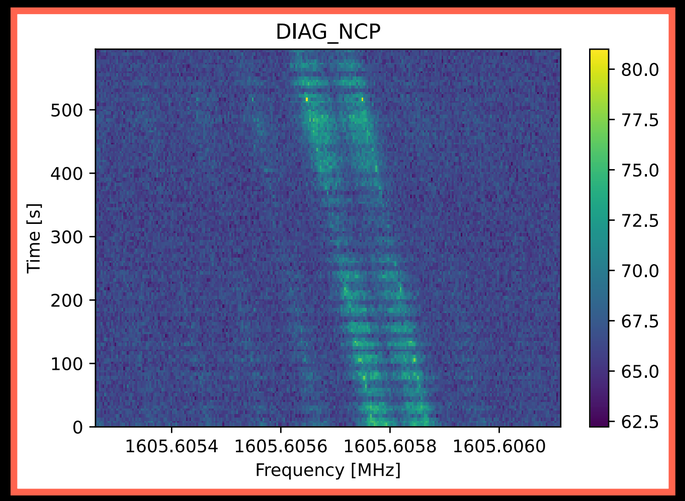
Analysis steps for a detected narrowband signal

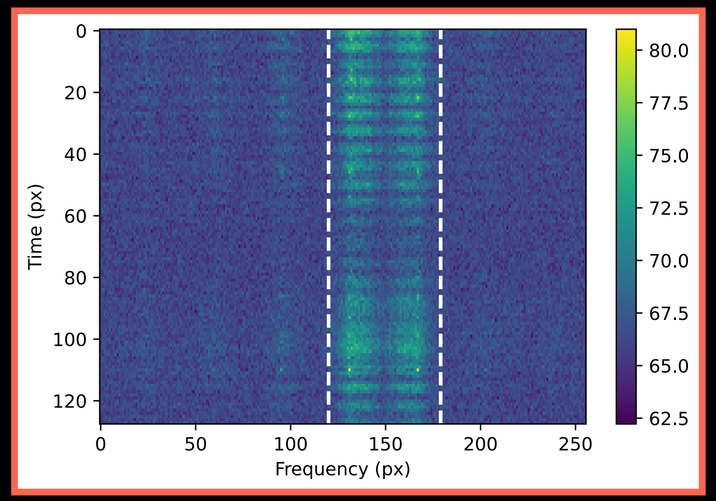


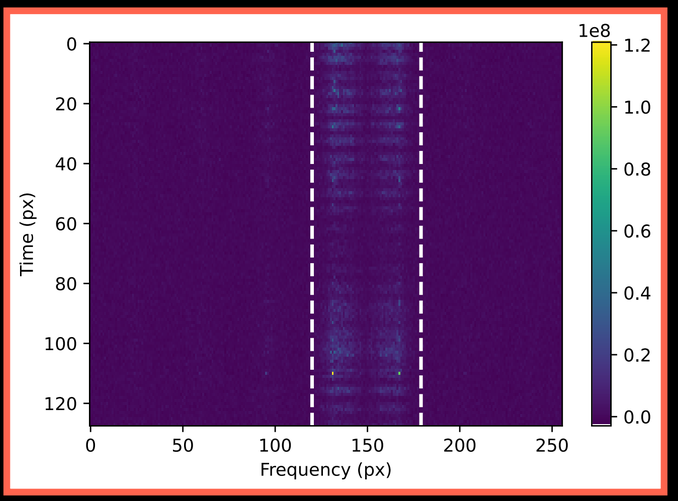
Analysis steps for a detected narrowband signal

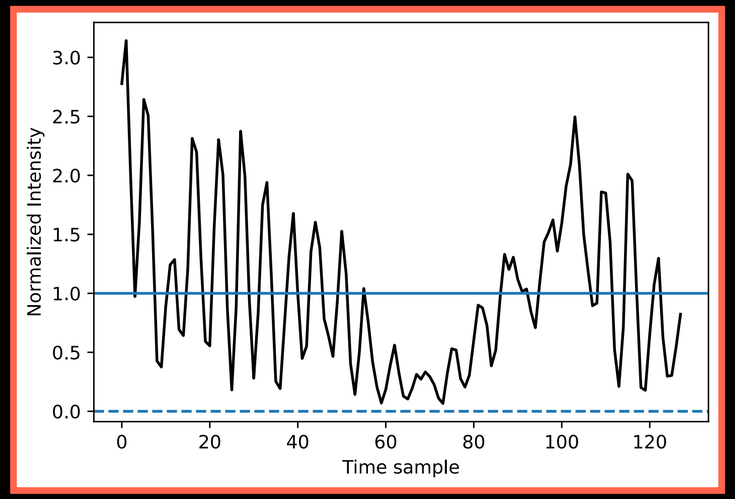


Analysis steps for a detected narrowband signal

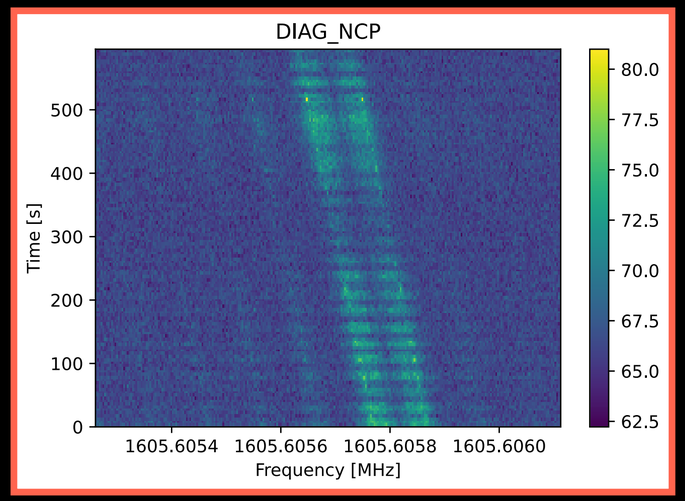


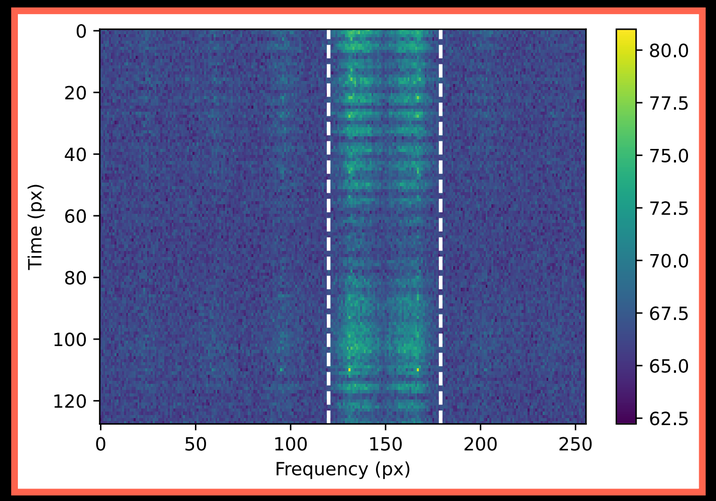


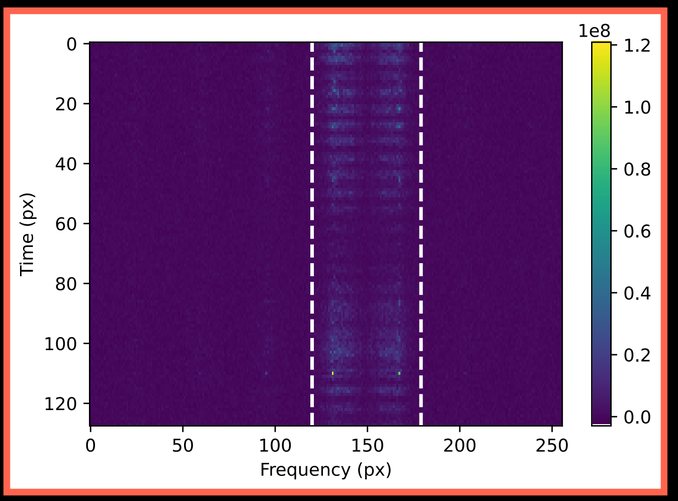


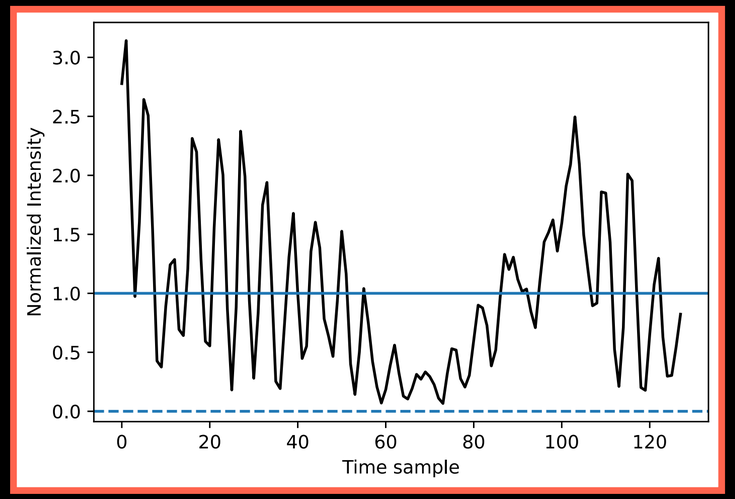


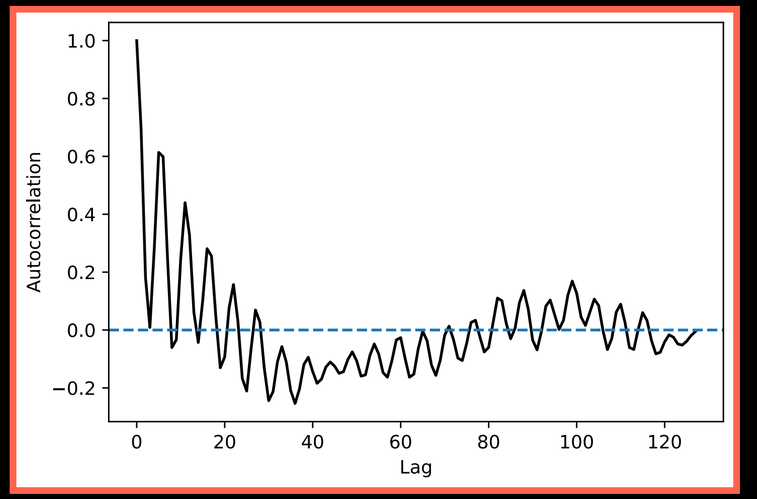
Analysis steps for a detected narrowband signal



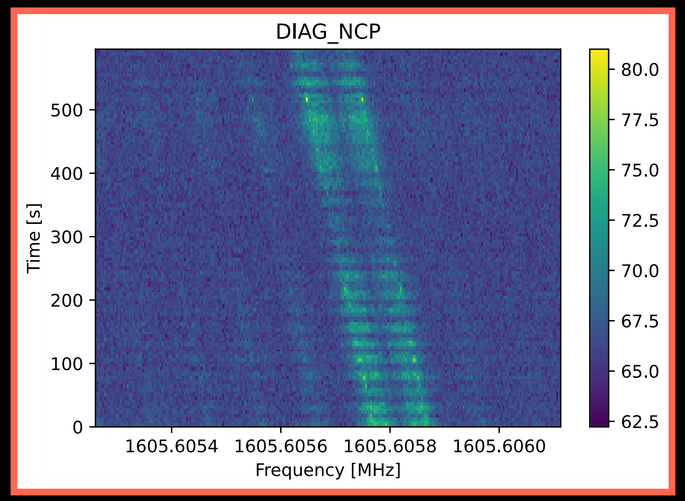


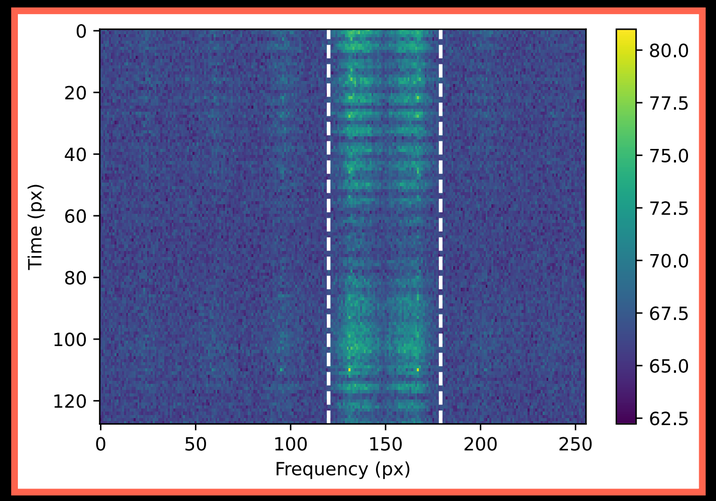


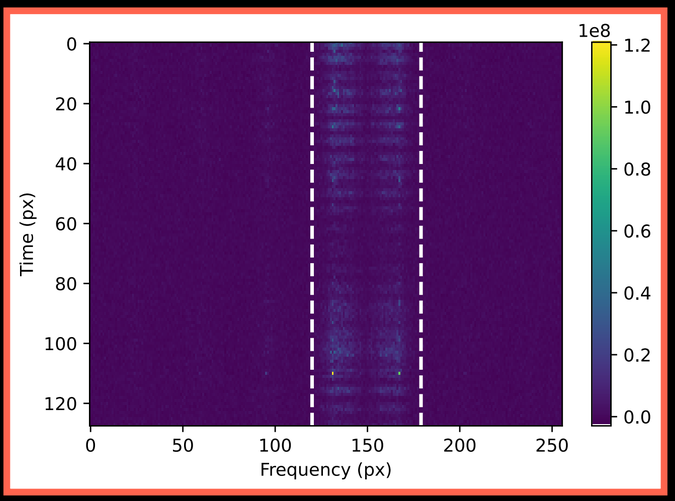


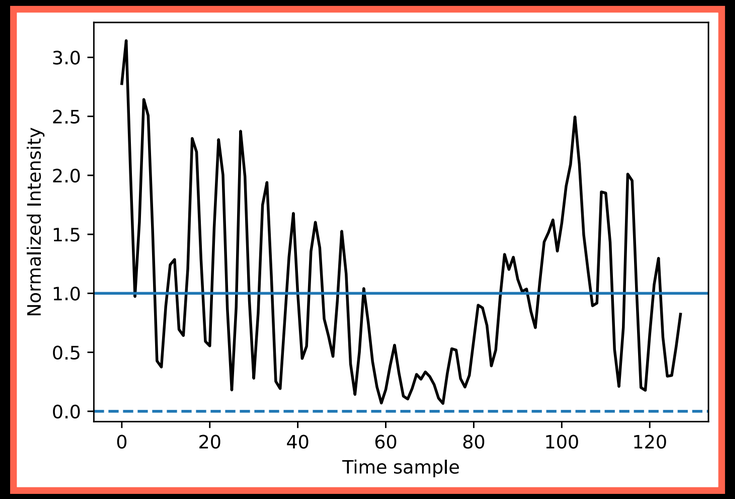


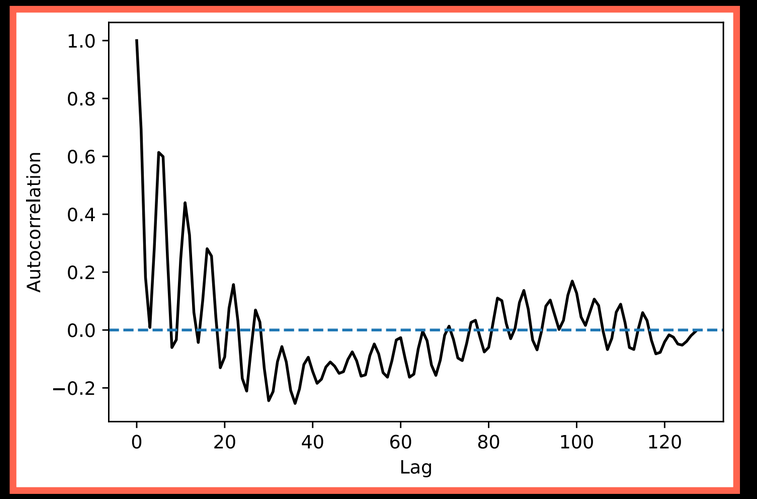
Analysis steps for a detected narrowband signal











Summary statistics

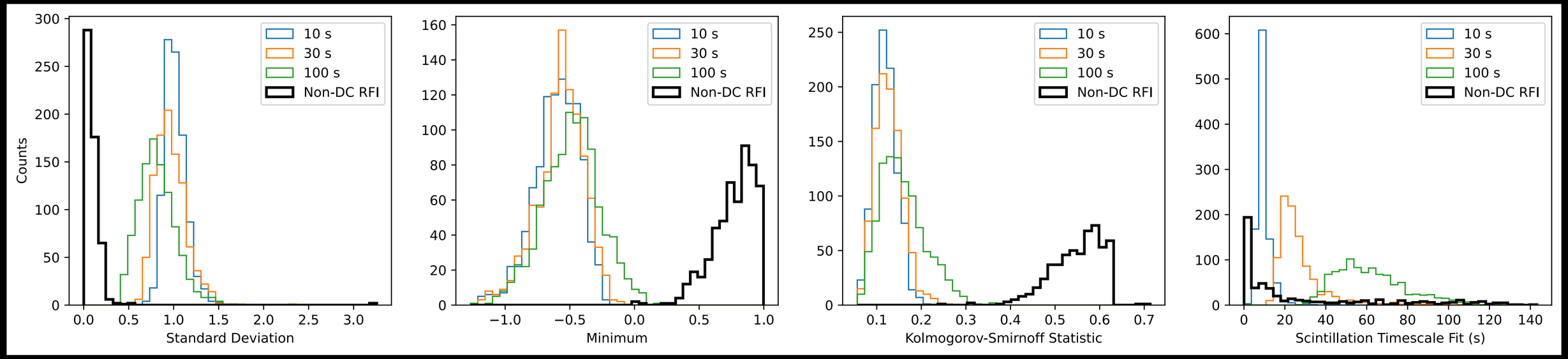
Set of summary statistics

Statistic	Asymptotic Value (with no background noise)	Target
Standard Deviation (RMS)	1	Exponential distribution
Minimum	0	Exponential distribution
Kolmogorov-Smirnoff statistic	0	Exponential distribution
Scintillation Timescale Fit with Least Squares	Variable	Near-Gaussian autocorrelation

GBT RFI vs. injected synthetic scintillated signals

C band (4 – 8 GHz)

S/N > 25



Standard Deviation

Minimum

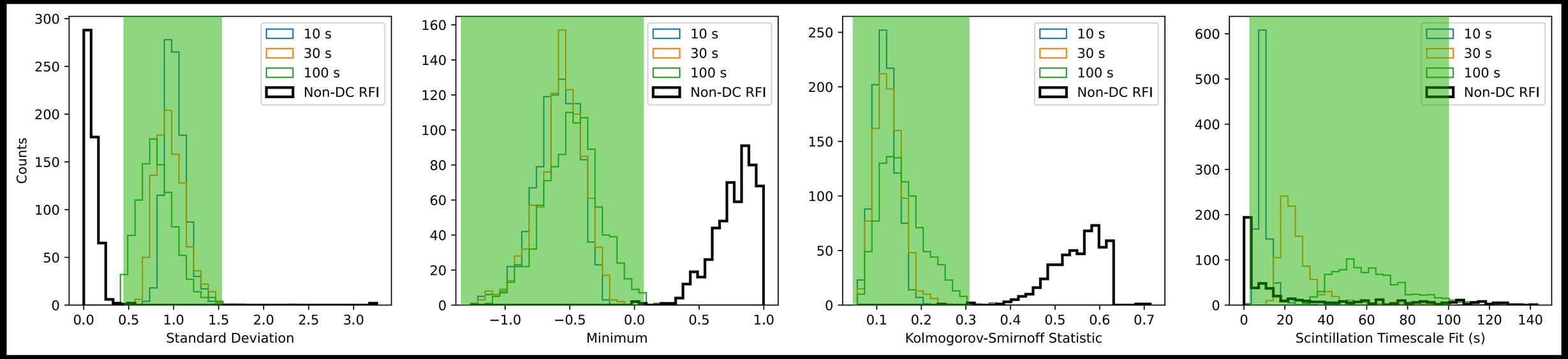
Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

GBT RFI vs. injected synthetic scintillated signals

C band (4 – 8 GHz)

S/N > 25



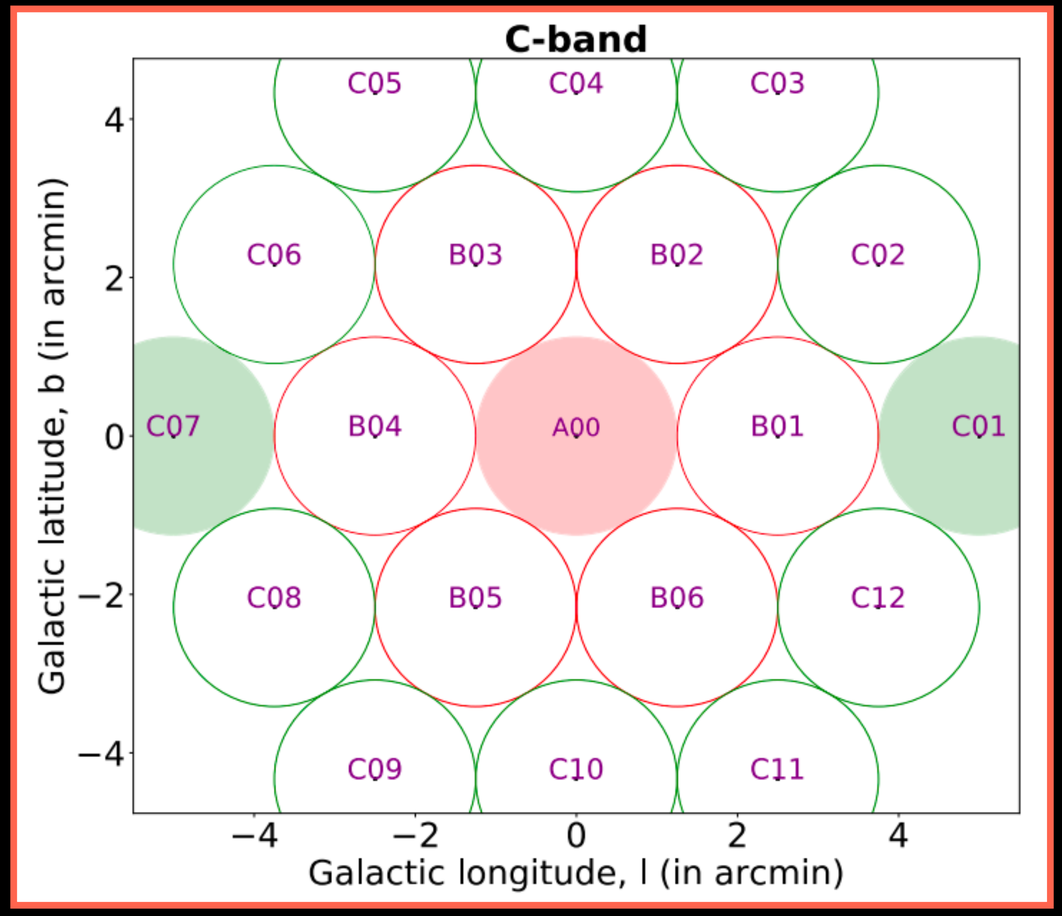
Standard Deviation

Minimum

Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

Planning Galactic center / plane observations



Gajjar et al. 2021

Planning Galactic center / plane observations

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

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T. Joseph W. Lazio
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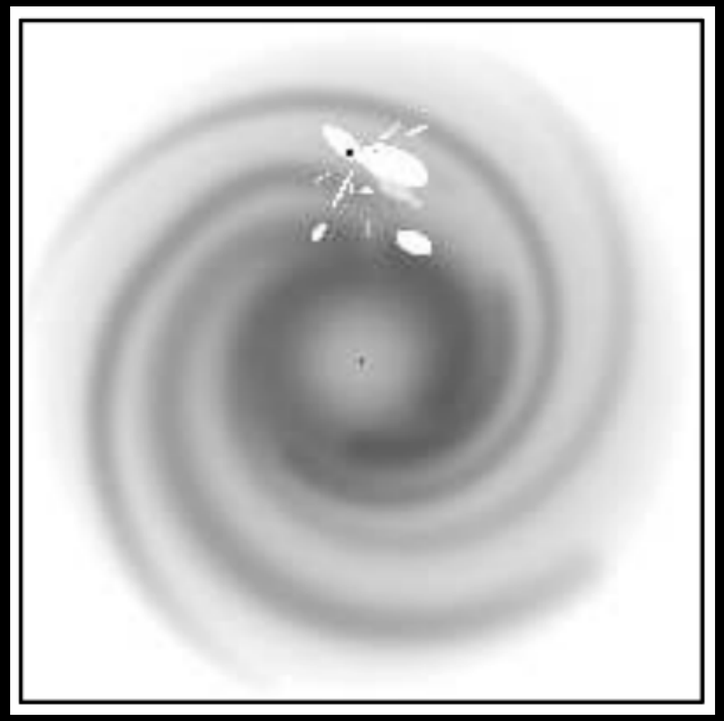
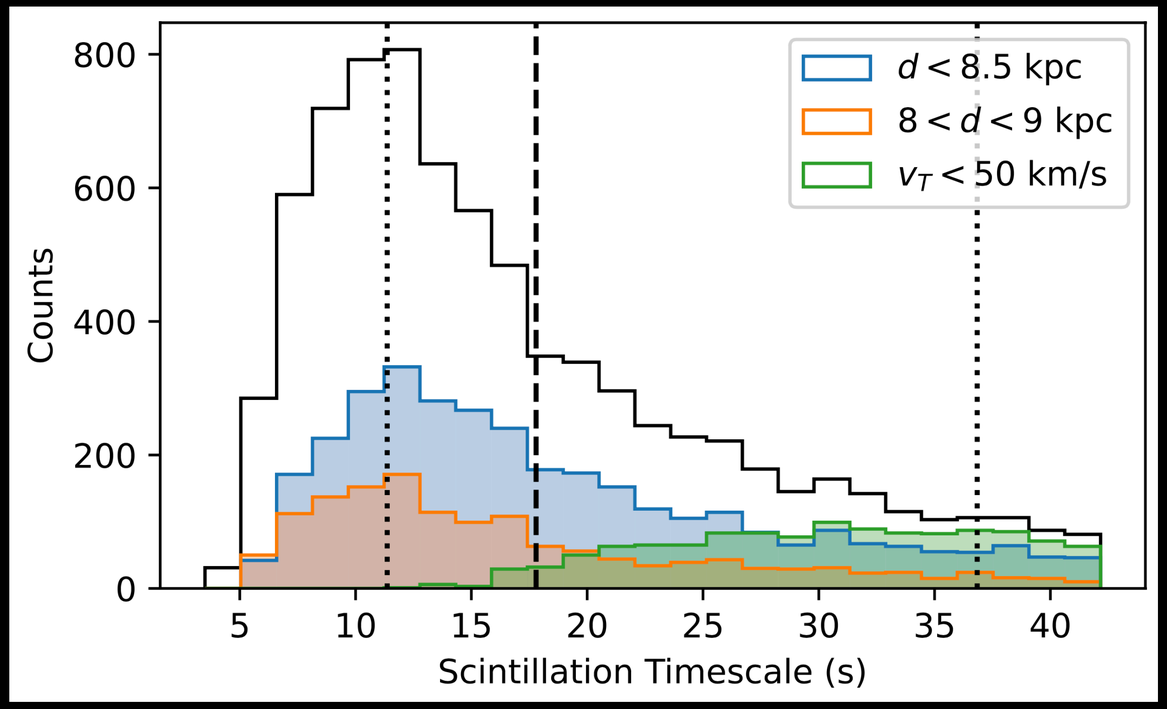


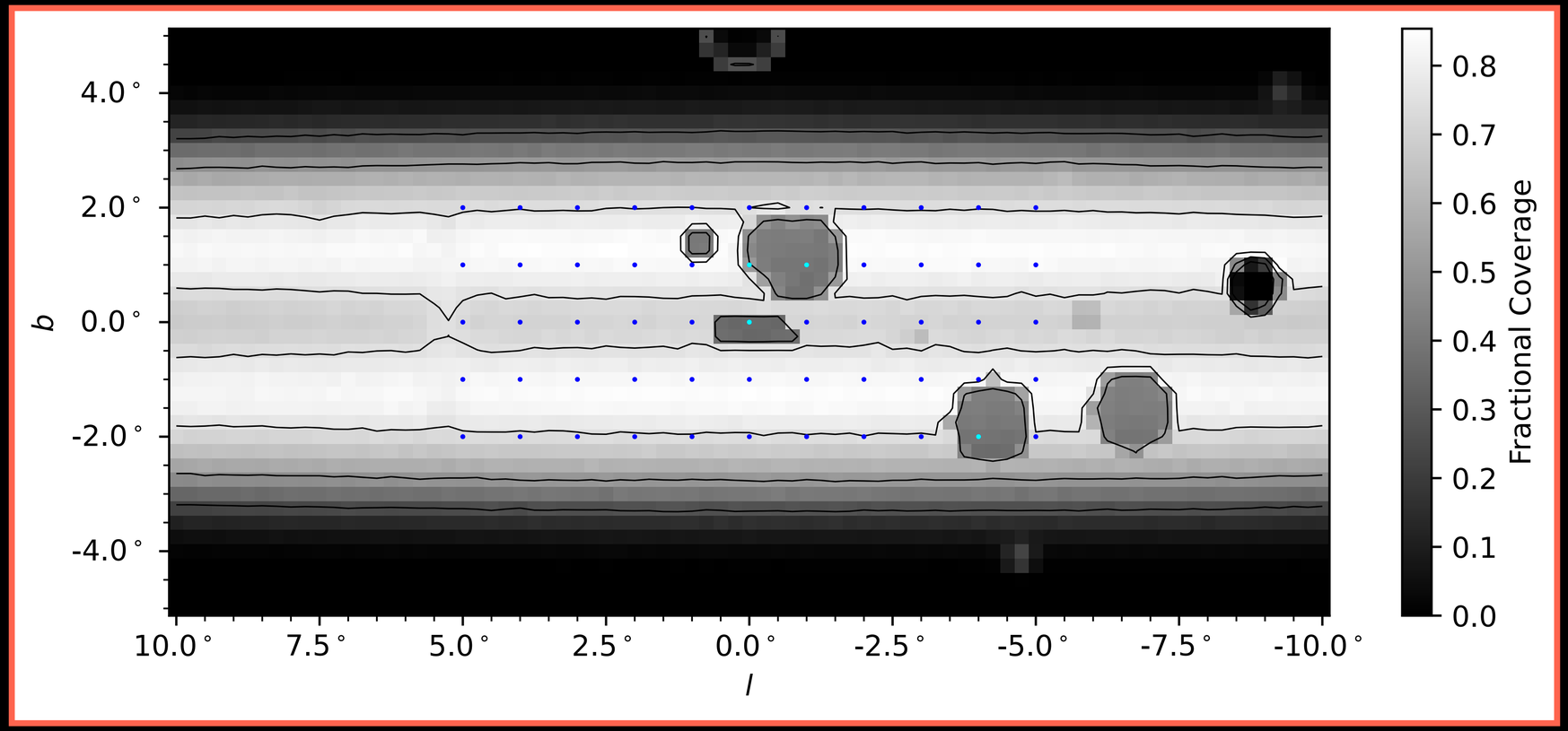
$$\Delta t_d \propto \nu^{6/5} v_T^{-1}$$



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

Planning Galactic center / plane observations

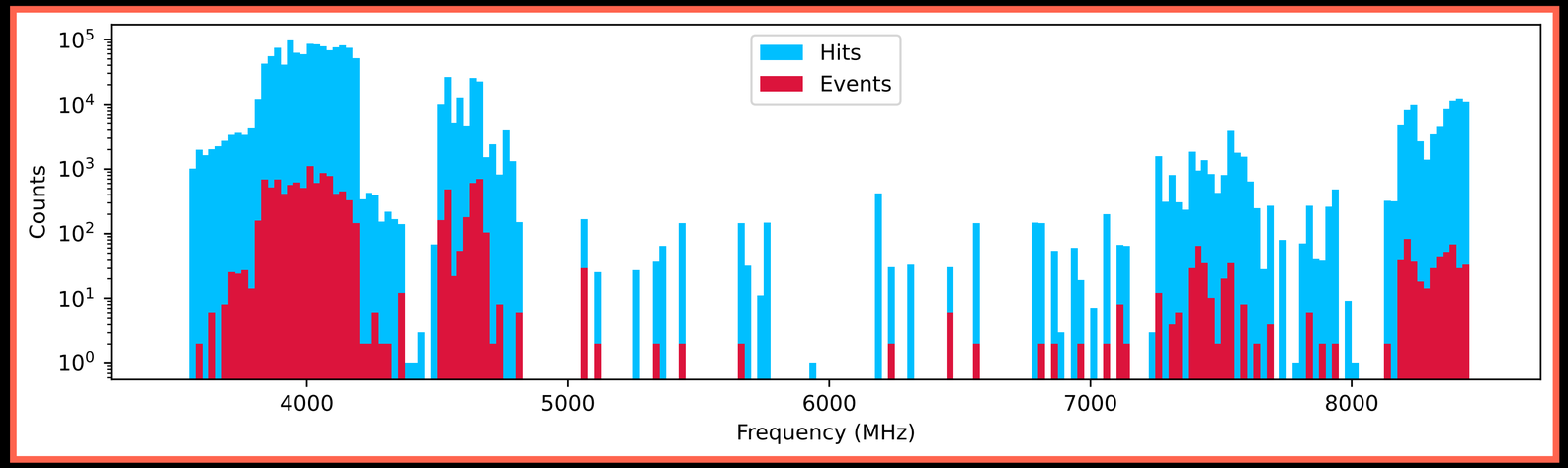
Fractional coverage for scintillation timescales between 10 s and 100 s

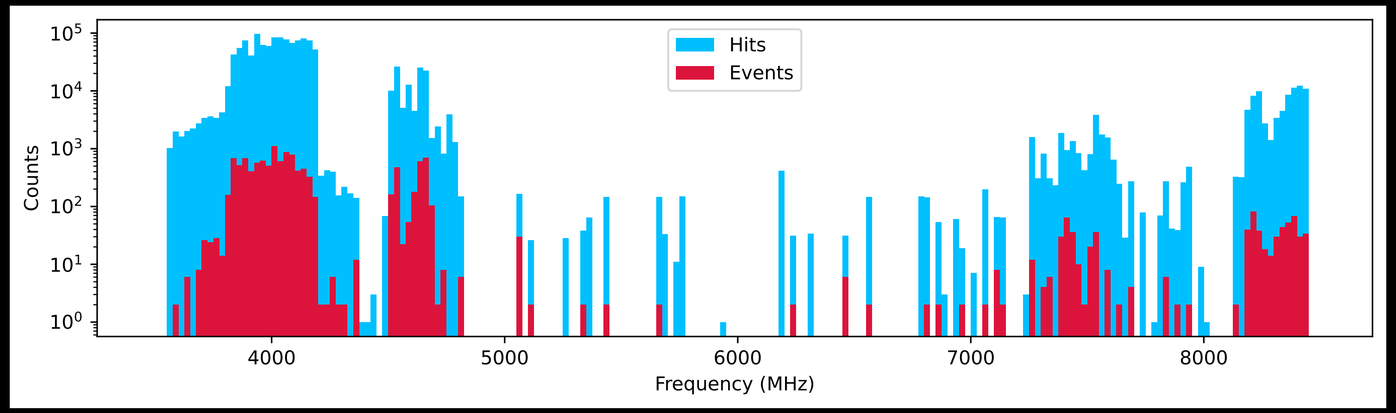


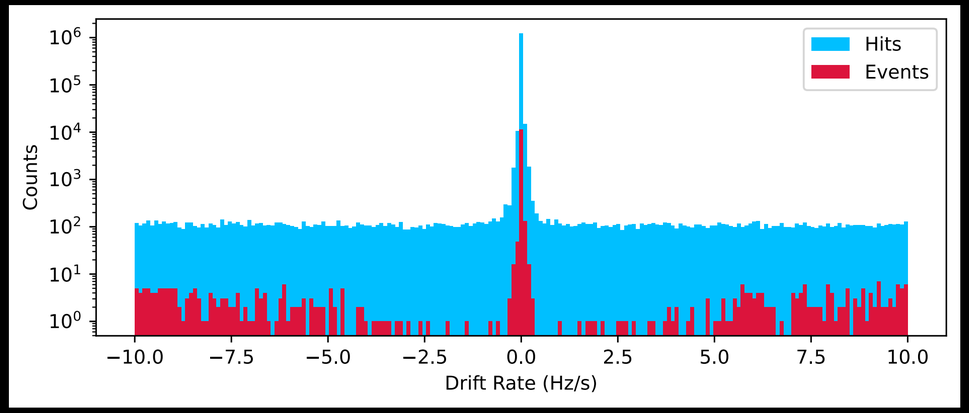
Brzycki et al. (in prep)

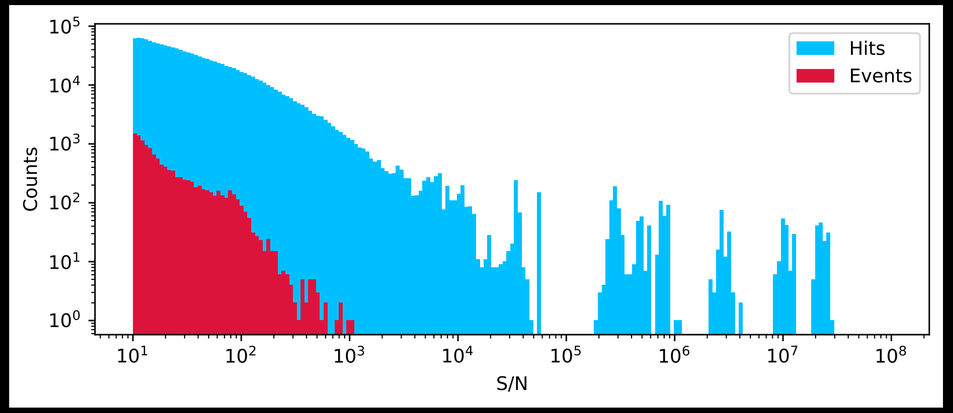
Scintillation survey towards the Galactic center / plane

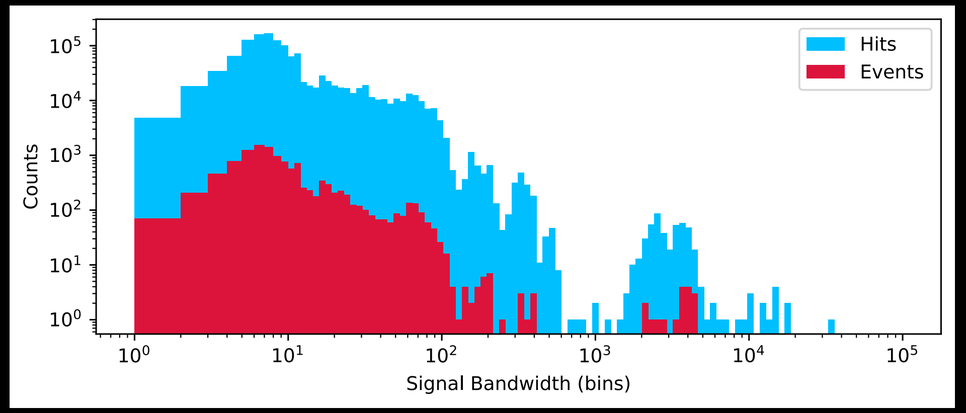
- ABAB cadences
- 10 minutes per observation
- 2.5 s, 2.8 Hz resolution
- 73 pointings in total, for about 24.3 hr of observations
- 1.3 million detected signals, 6018 “events” passed ON-OFF filtering

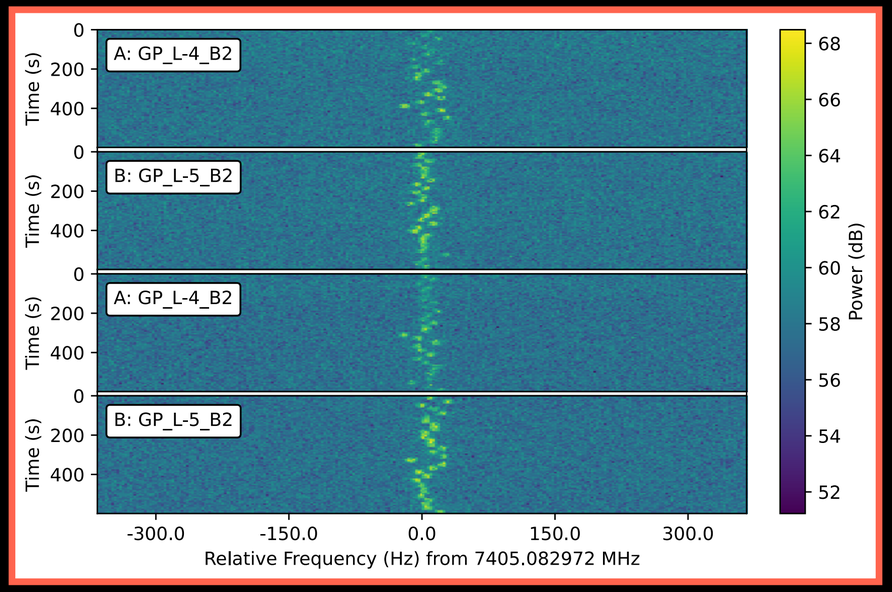


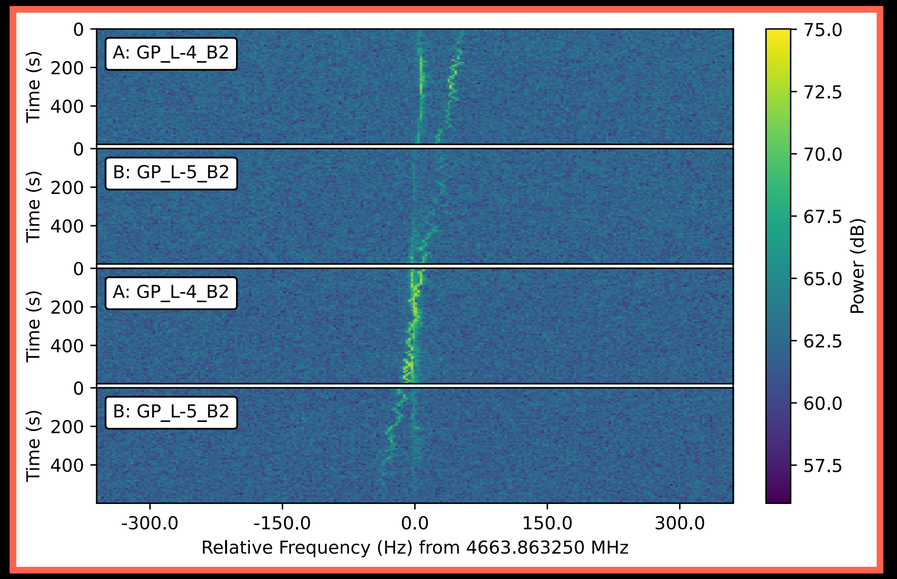

Hits
Events
Counts
Frequency (MHz)
4000
5000
6000
7000
8000

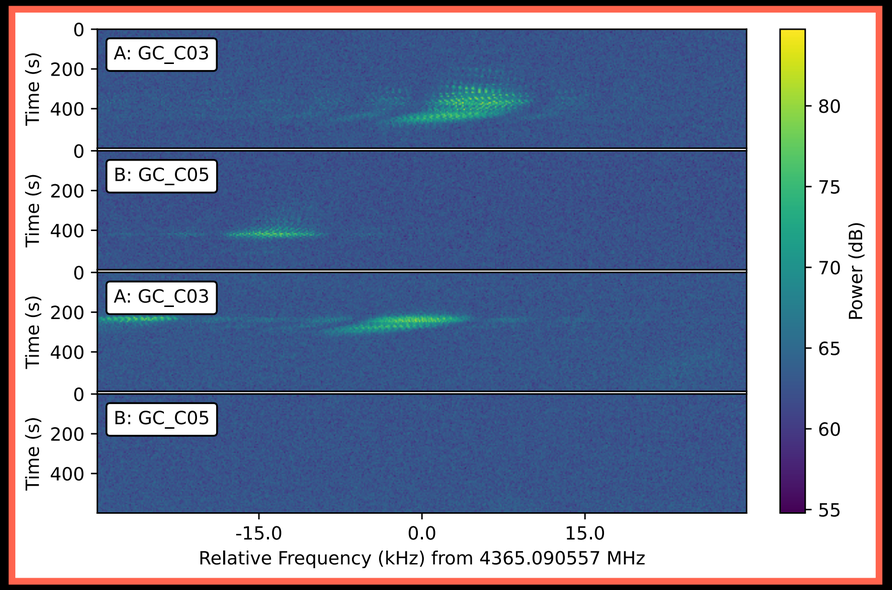

Hits
Events
Counts
Drift Rate (Hz/s)
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0

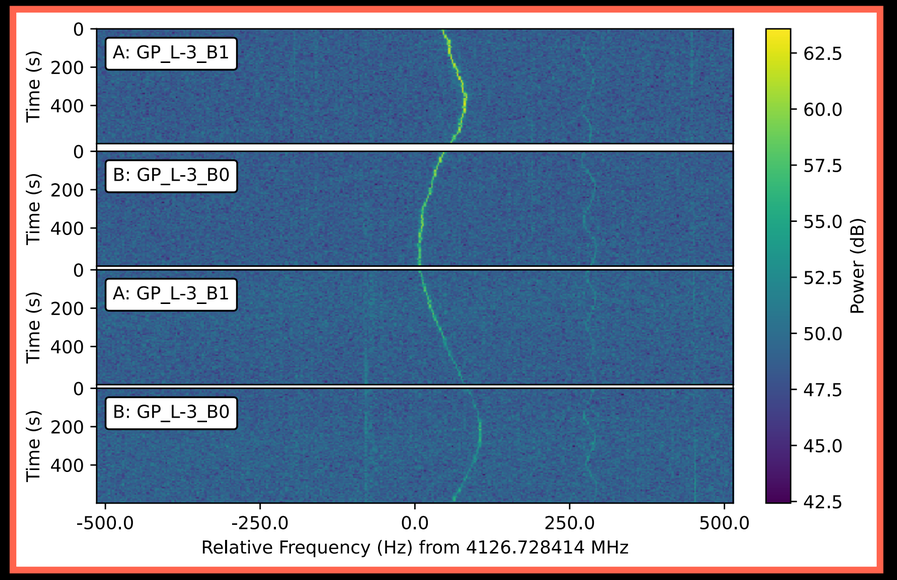

Hits
Events
Counts
S/N


Hits
Events
Counts
Signal Bandwidth (bins)

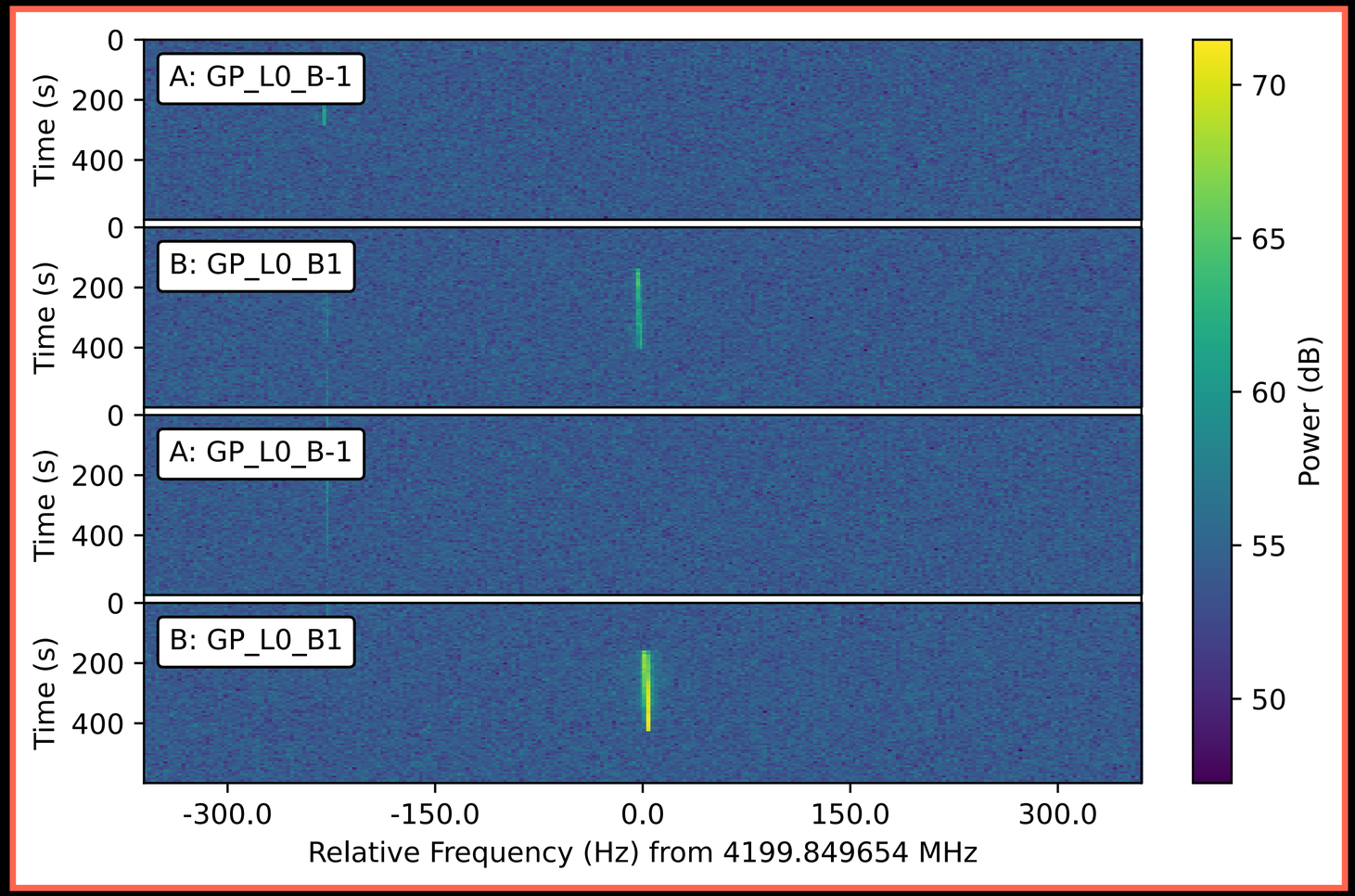

A: GP_L-4_B2
B: GP_L-5_B2
A: GP_L-4_B2
B: GP_L-5_B2
Time (s)
0
200
400
-300.0
-150.0
0.0
150.0
300.0
Relative Frequency (Hz) from 7405.082972 MHz
Power (dB)
68
66
64
62
60
58
56
54
52

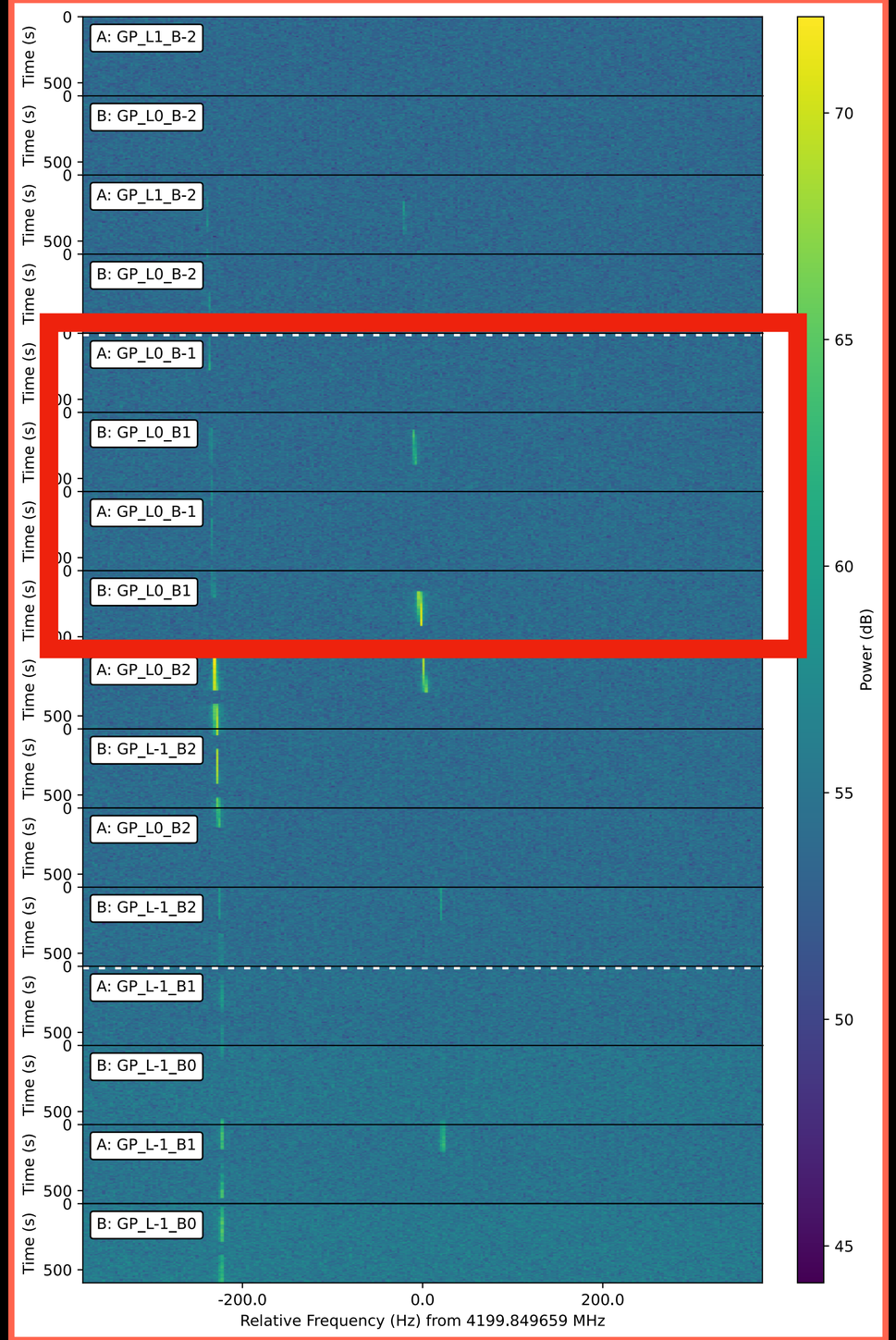

A: GP_L-4_B2
B: GP_L-5_B2
A: GP_L-4_B2
B: GP_L-5_B2
Time (s)
0
200
400
-300.0
-150.0
0.0
150.0
300.0
Relative Frequency (Hz) from 4663.863250 MHz
Power (dB)
75.0
72.5
70.0
67.5
65.0
62.5
60.0
57.5


A: GC_C03
B: GC_C05
A: GC_C03
B: GC_C05
Time (s)
0
200
400
-15.0
0.0
15.0
Relative Frequency (kHz) from 4365.090557 MHz
Power (dB)
80
75
70
65
60
55

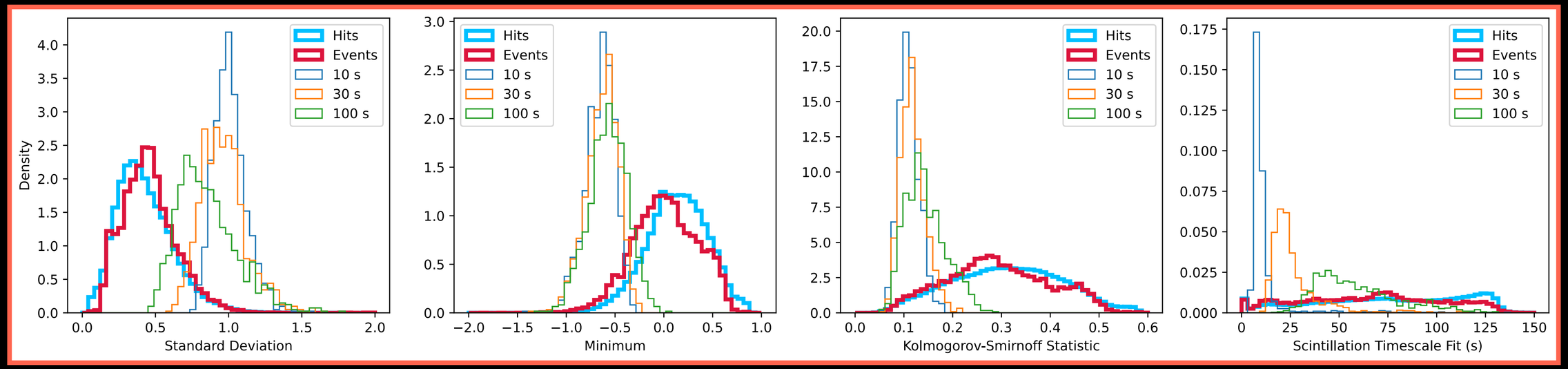

A: GP_L-3_B1
B: GP_L-3_B0
A: GP_L-3_B1
B: GP_L-3_B0
Time (s)
0
200
400
-500.0
-250.0
0.0
250.0
500.0
Relative Frequency (Hz) from 4126.728414 MHz
Power (dB)
62.5
60.0
57.5
55.0
52.5
50.0
47.5
45.0
42.5

Best candidate event we found




A: GP_L1_B-2
B: GP_L0_B-2
A: GP_L1_B-2
B: GP_L0_B-2
A: GP_L0_B-1
B: GP_L0_B1
A: GP_L0_B-1
B: GP_L0_B1
A: GP_L0_B2
B: GP_L-1_B2
A: GP_L0_B2
B: GP_L-1_B2
A: GP_L-1_B1
B: GP_L-1_B0
A: GP_L-1_B1
B: GP_L-1_B0
Time (s)
0
500
-200.0
0.0
200.0
Relative Frequency (Hz) from 4199.849659 MHz
Power (dB)
70
65
60
55
50
45

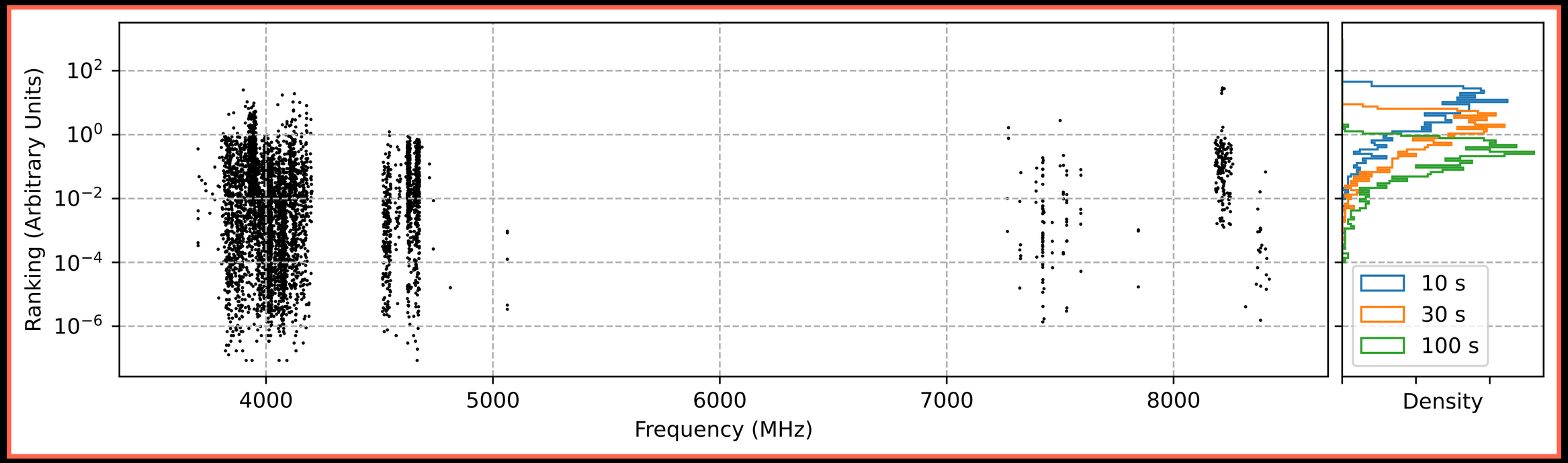
Manual inspection turned up no true candidates... so can RFI look like scintillation?



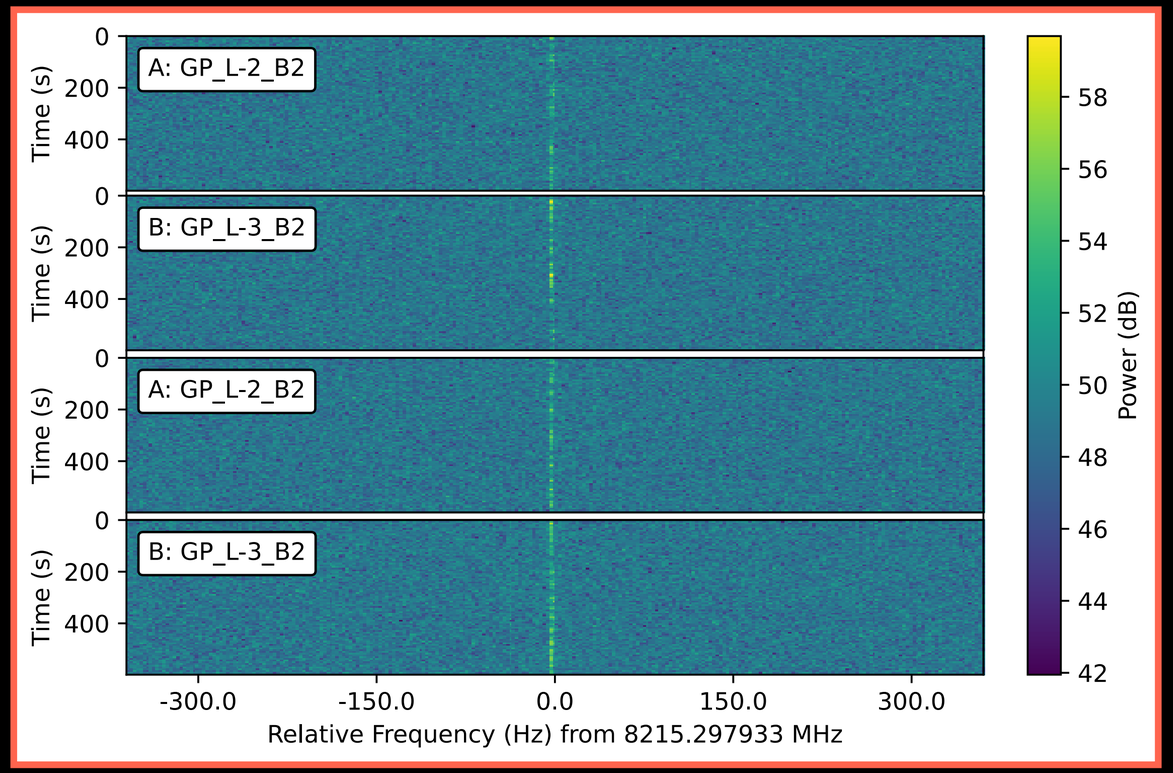
Empirical PDFs for detected signals vs. injected synthetic scintillated signals with timescales of 10, 30, 100 s

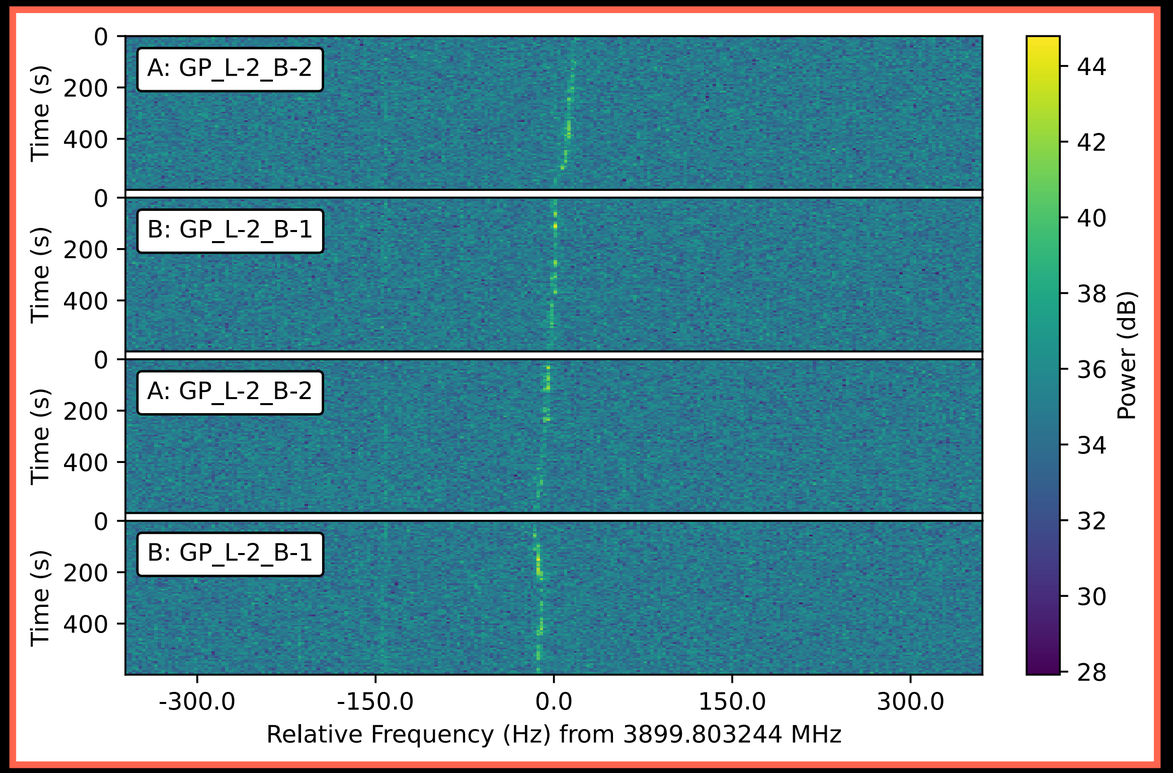
Simple score for ranking signals

$$w(\mathbf{h}, \Delta t_d) = p_{\mathrm{std}}(h_{\mathrm{std}}, \Delta t_d) \times p_{\mathrm{min}}(h_{\mathrm{min}}, \Delta t_d) \times p_{\mathrm{KS}}(h_{\mathrm{KS}}, \Delta t_d) \times p_{\mathrm{fit}}(h_{\mathrm{fit}}, \Delta t_d).$$



Example events with high scintillation scores

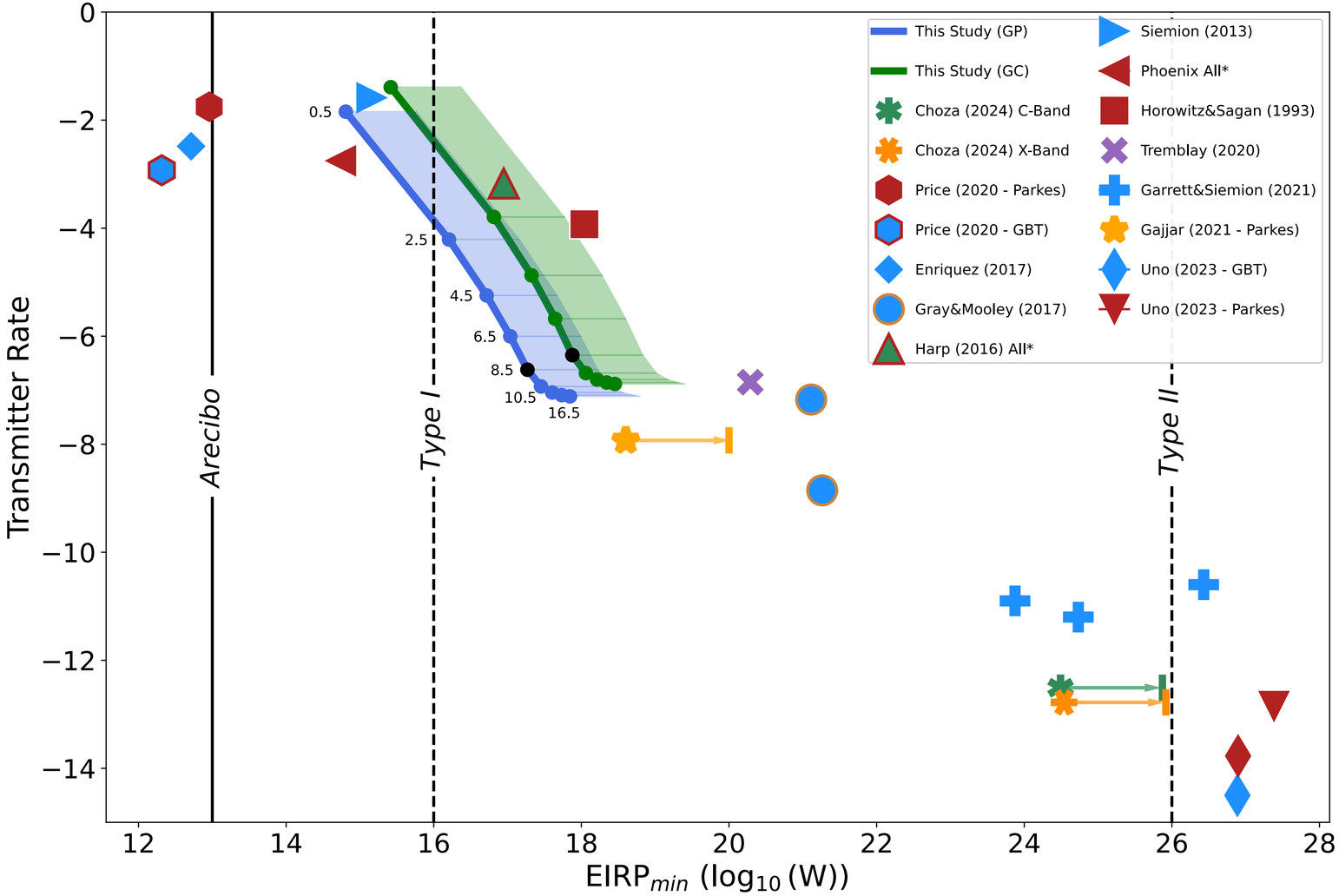




Some takeaways

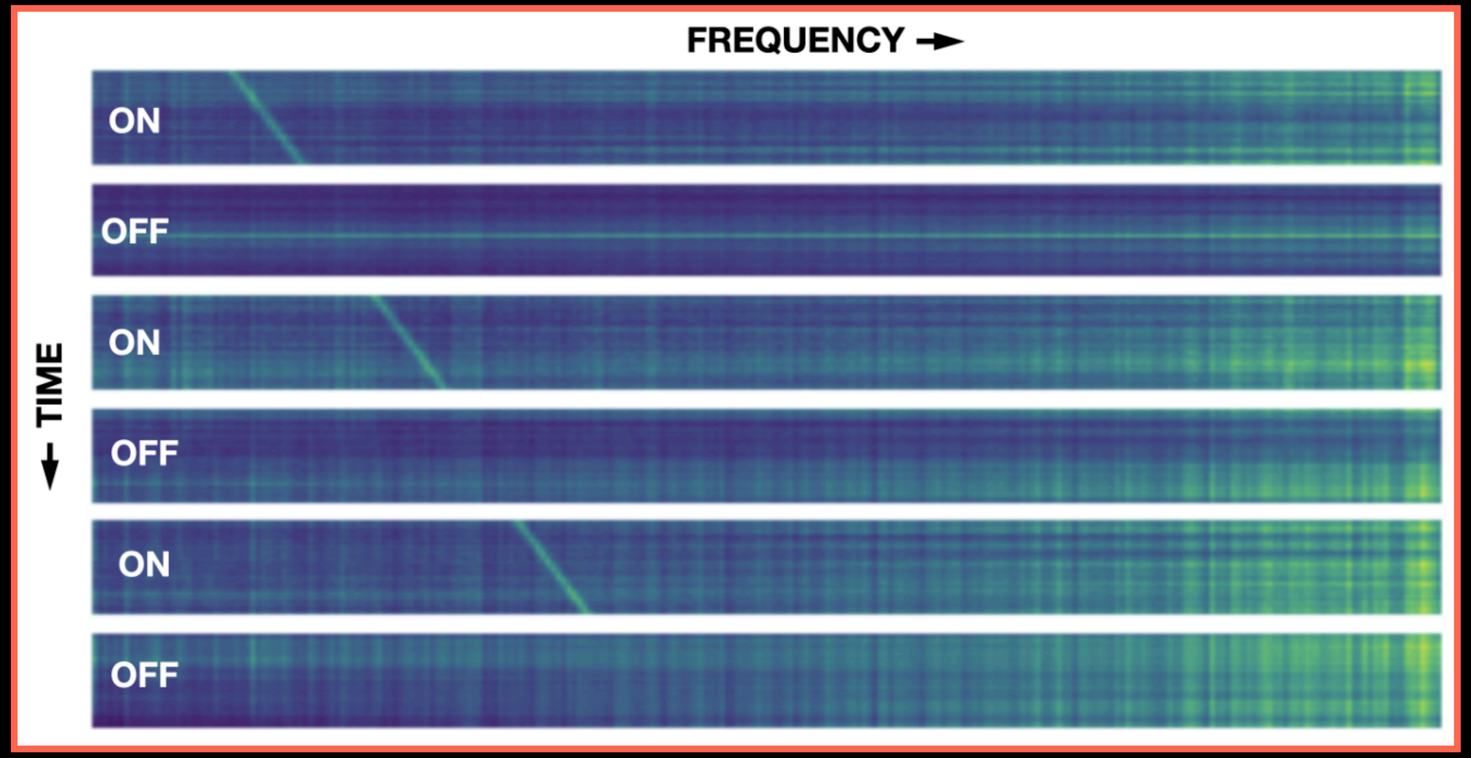
- Unfortunately, no candidates, scintillated or otherwise, passed all filters in our survey of the Galactic center and Galactic plane
- For sources up to a distance of 8.5 kpc, we set a limit for the equivalent isotropic radiated power of ~2e17 W (1e4 times larger than Arecibo)
- Until we get a much deeper understanding of the RFI environment around our telescopes, the ON-OFF filter will likely remain the most reliable indicator

Extra Slides


This Study (GP)
This Study (GC)
Choza (2024) C-Band
Choza (2024) X-Band
Price (2020 - Parkes)
Price (2020 - GBT)
Enriquez (2017)
Gray&Mooley (2017)
Harp (2016) All*
Siemion (2013)
Phoenix All*
Horowitz&Sagan (1993)
Tremblay (2020)
Garrett&Siemion (2021)
Gajjar (2021 - Parkes)
Uno (2023 - GBT)
Uno (2023 - Parkes)
0.5
2.5
4.5
6.5
8.5
10.5
16.5
Arecibo
Type I
Type II
Transmitter Rate
EIRP$_{min}$ (log$_{10}$ (W))
0
−2
−4
−6
−8
−10
−12
−14
12
14
16
18
20
22
24
26
28

Other people actually use Setigen!

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

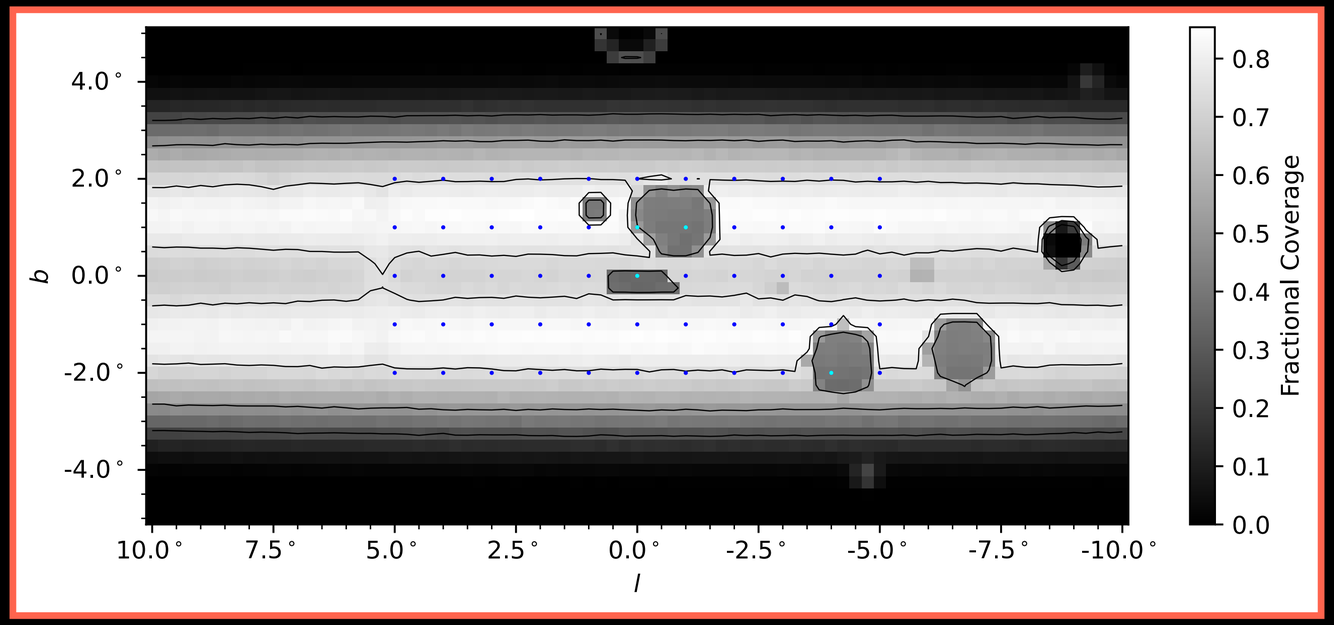


Breakthrough Listen x Kaggle 2021

Planning Galactic center / plane observations

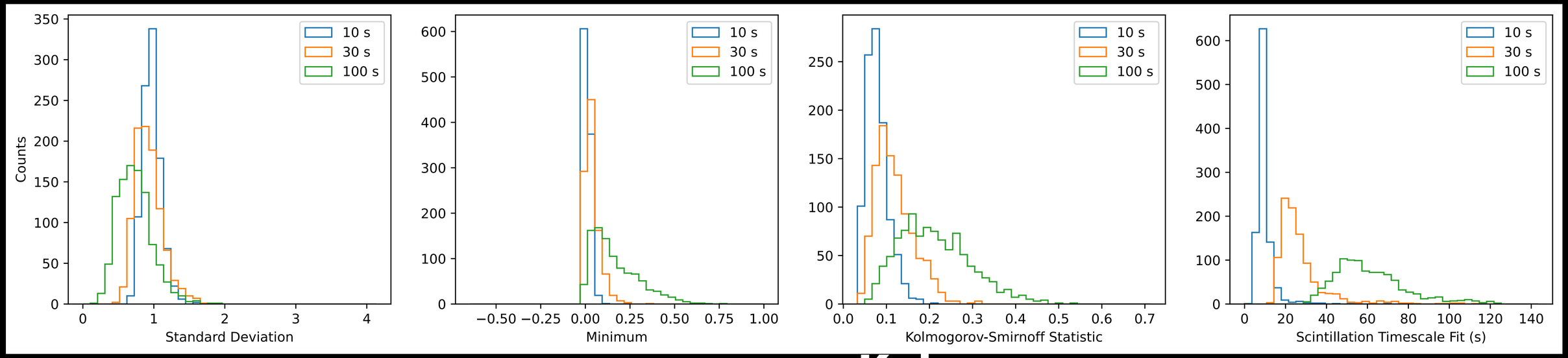
- Estimate most likely scintillation timescales using NE2001 model (Cordes & Lazio 2002) and scale by Monte Carlo sampling different possible physical configurations

Fractional coverage for scintillation timescales between 10 s and 100 s



Statistics using synthetic scintillated intensities (no noise)

600 s “observation”, 4.65 s resolution



Standard Deviation

Minimum

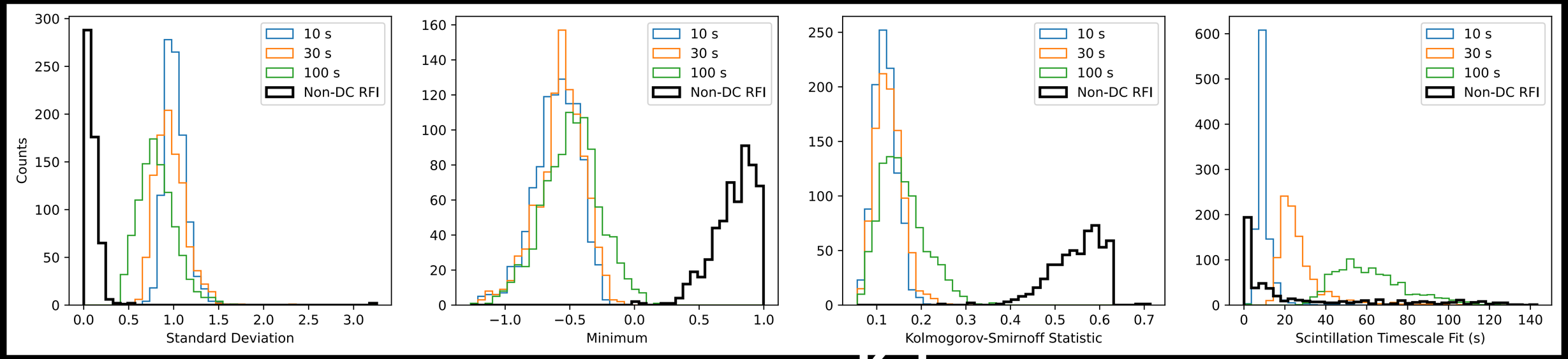
Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

GBT RFI vs. injected synthetic scintillated signals

C band (4 – 8 GHz)

S/N > 25



Standard Deviation

Minimum

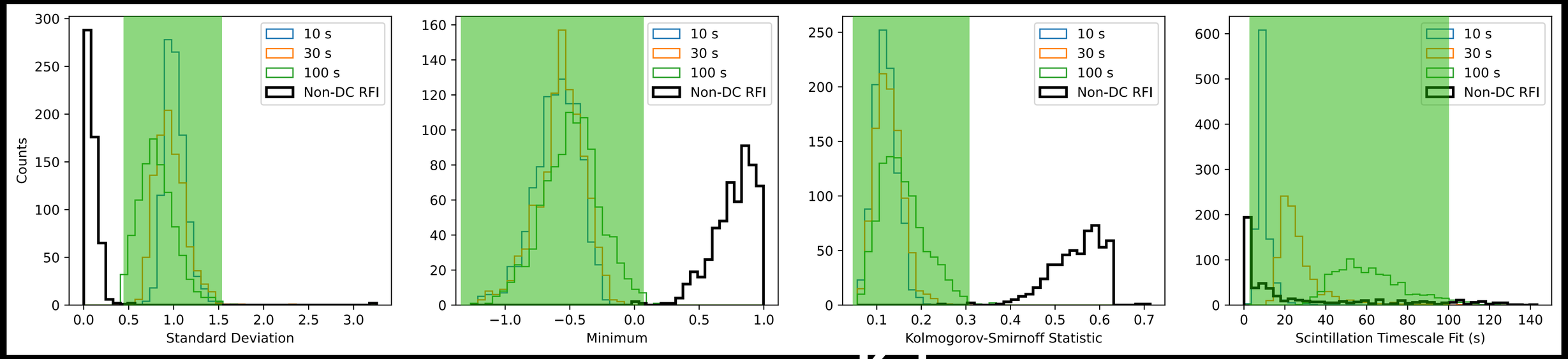
Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

GBT RFI vs. injected synthetic scintillated signals

C band (4—8 GHz)

S/N > 25



Standard Deviation

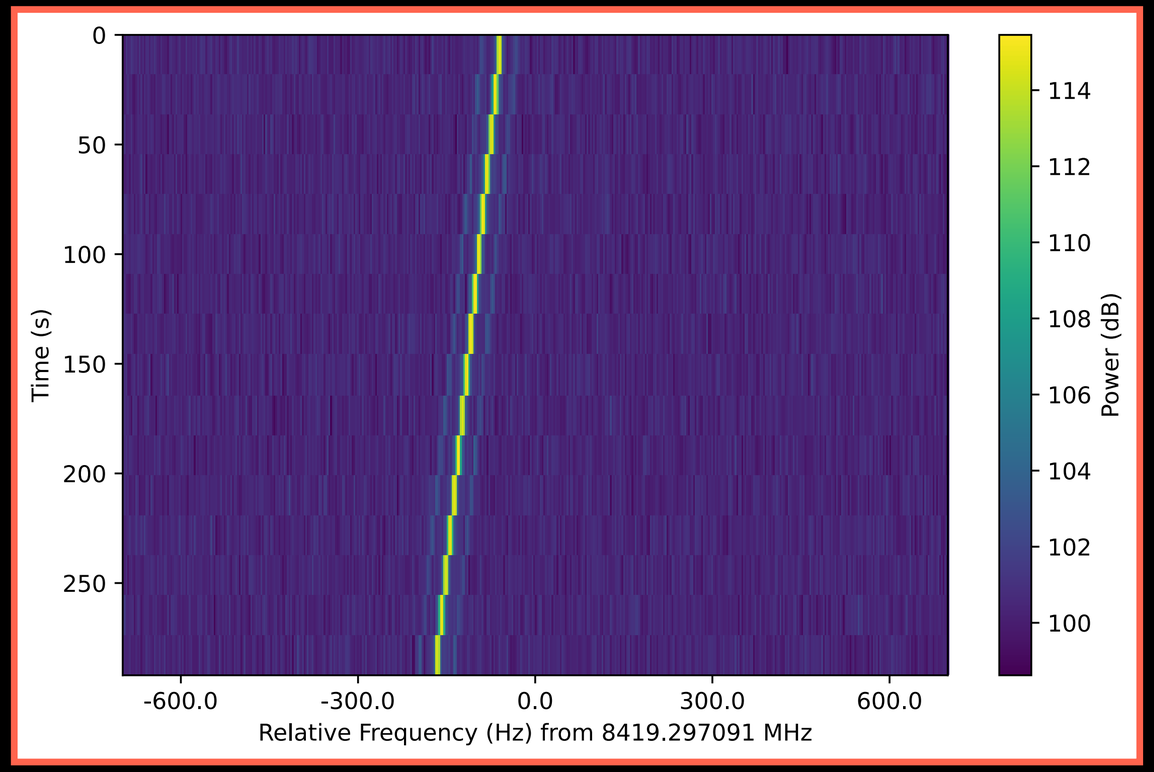
Minimum

Kolmogorov-Smirnoff Statistic

Scintillation Timescale Fit

Basic signal detection

- **Incoherent deDoppler (TurboSETI)**
- **Energy detection**
- **Machine learning (ML)**

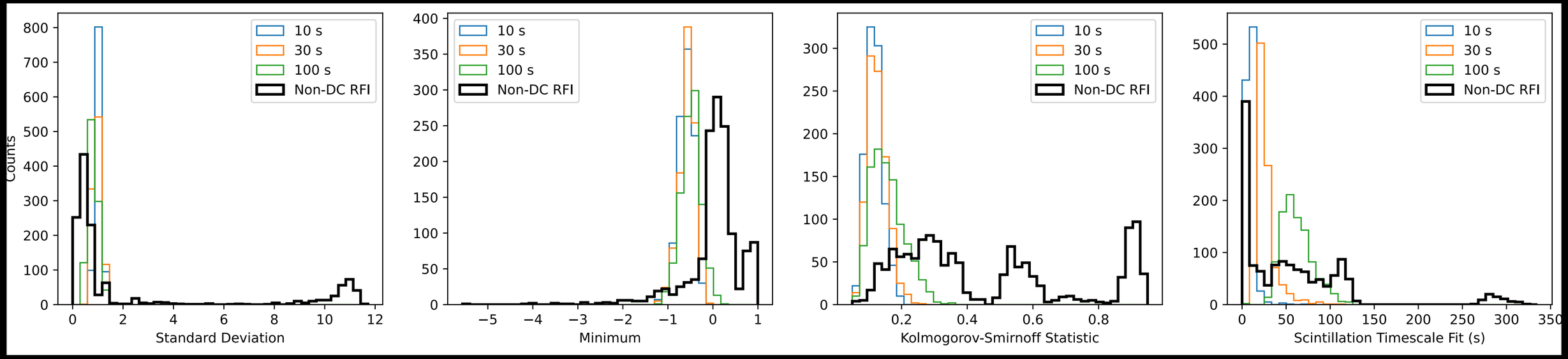


Detected signal from Voyager 1

GBT RFI vs. injected synthetic scintillated signals

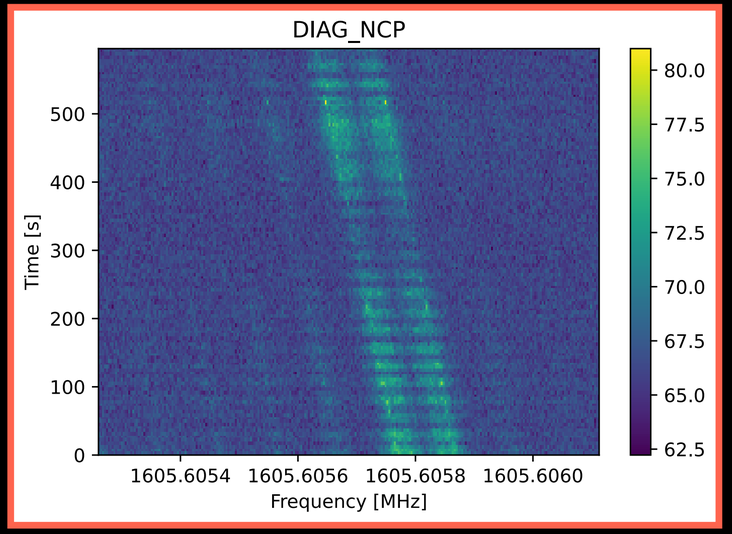
L band (1—2 GHz)

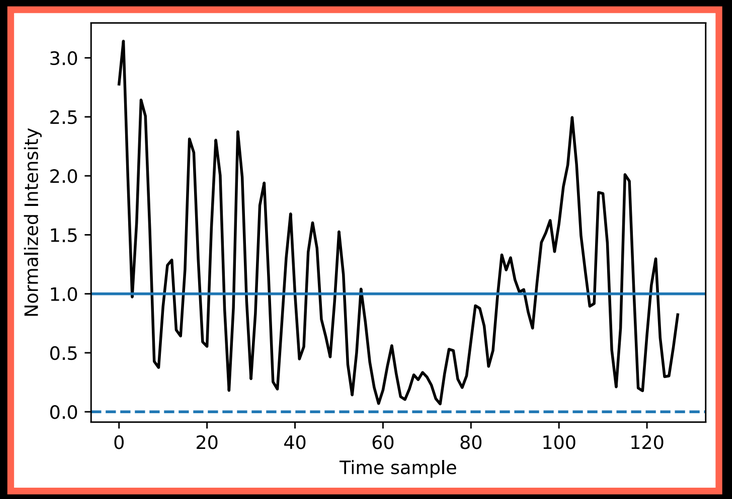
S/N > 25



How might we detect scintillations?

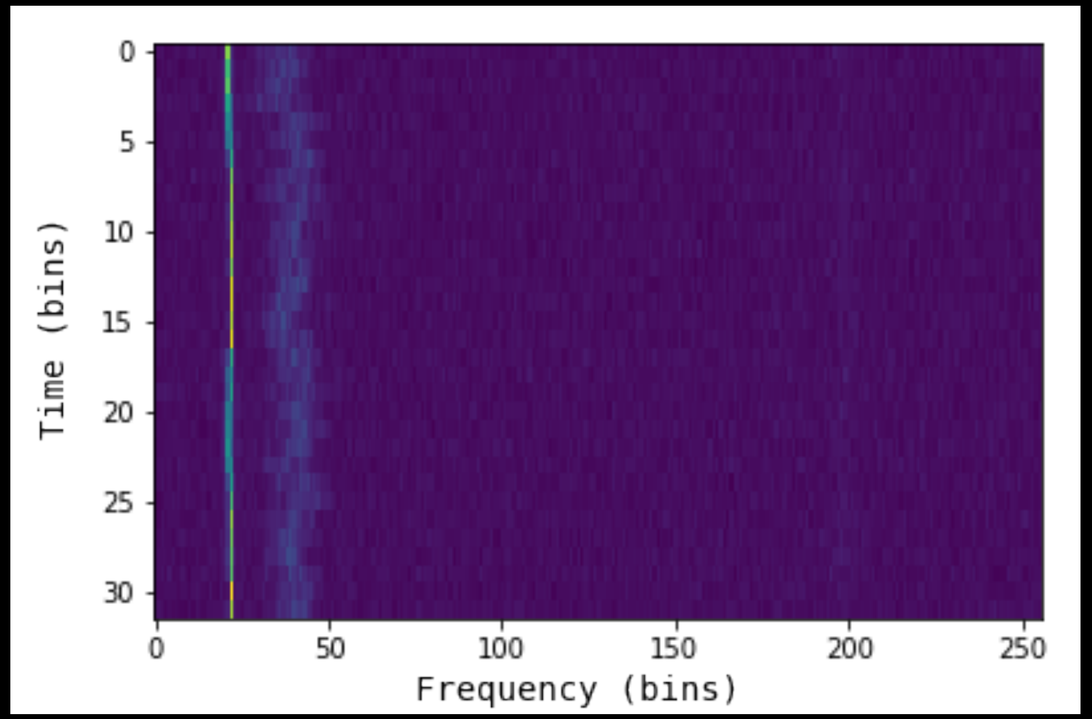
- Estimate intensity time series from signals detected with deDoppler methods
- Since scintillation is stochastic, identify summary statistics that probe asymptotic behavior
- Would existing RFI modulation confound real scintillation?
    - Create synthetic scintillated time series
    - Compare statistics of detected signals with those of synthetic scintillated signals





Narrowband signal localization with machine learning

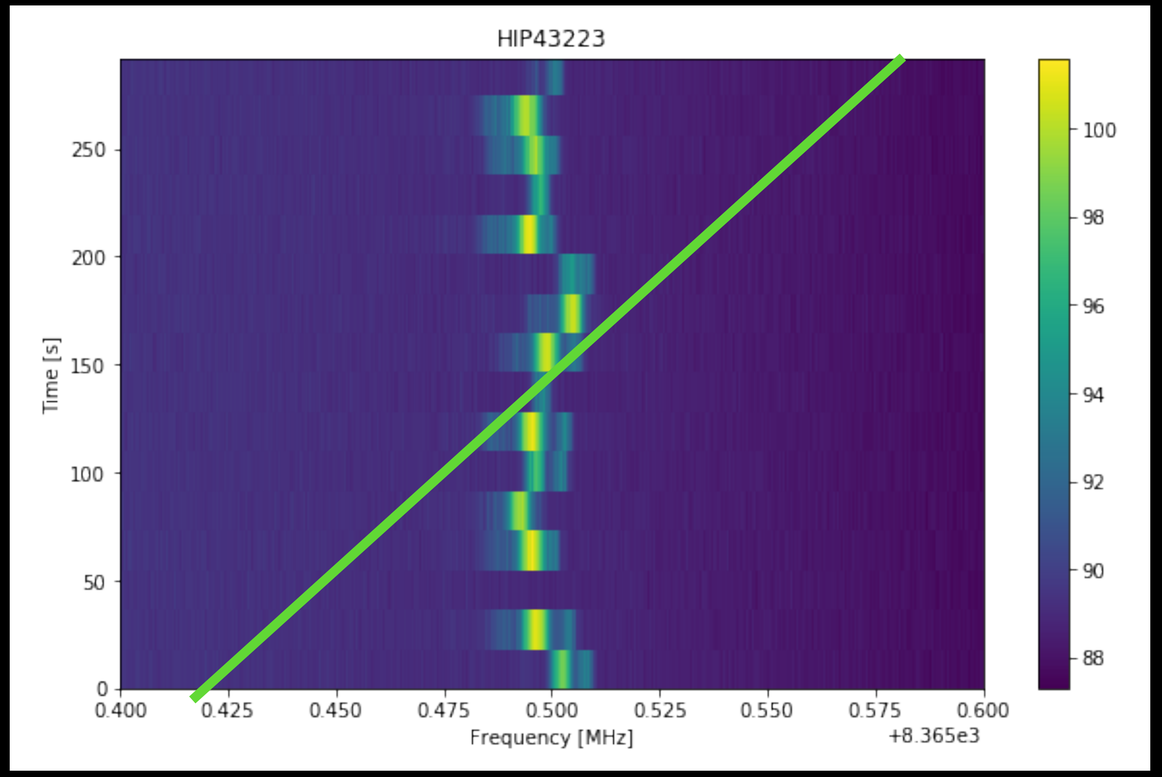
- Standard deDoppler pipeline:
  - Dim signals concealed by nearby bright signals
  - Computationally expensive to search high drift rates



Small snippet of GBT data at C-band

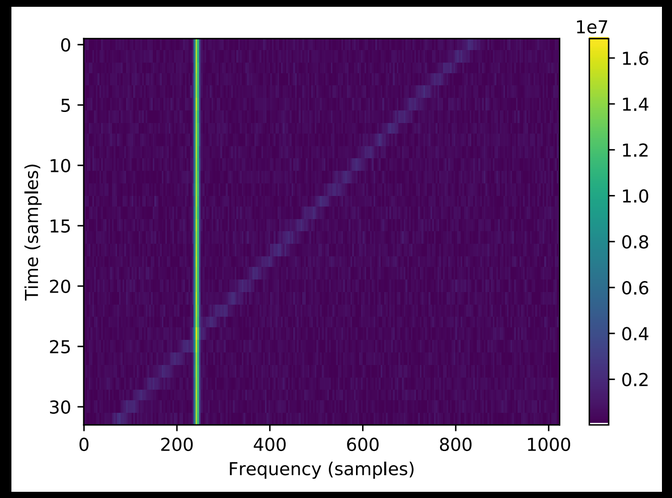
Brzycki et al. 2020,

- **Masking?**

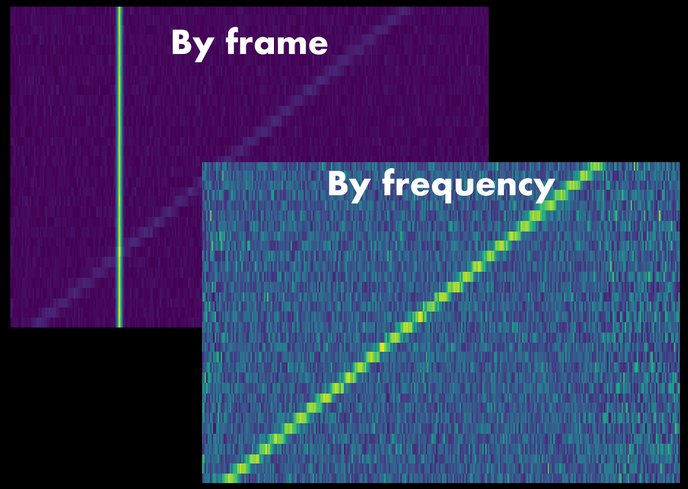


Brzycki et al. 2020,

Synthetic training data



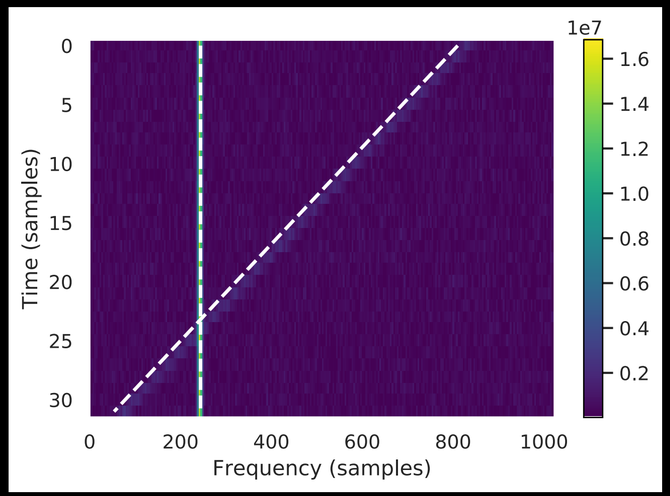
Normalization



- 1 or 2 signals per input

Neural Network

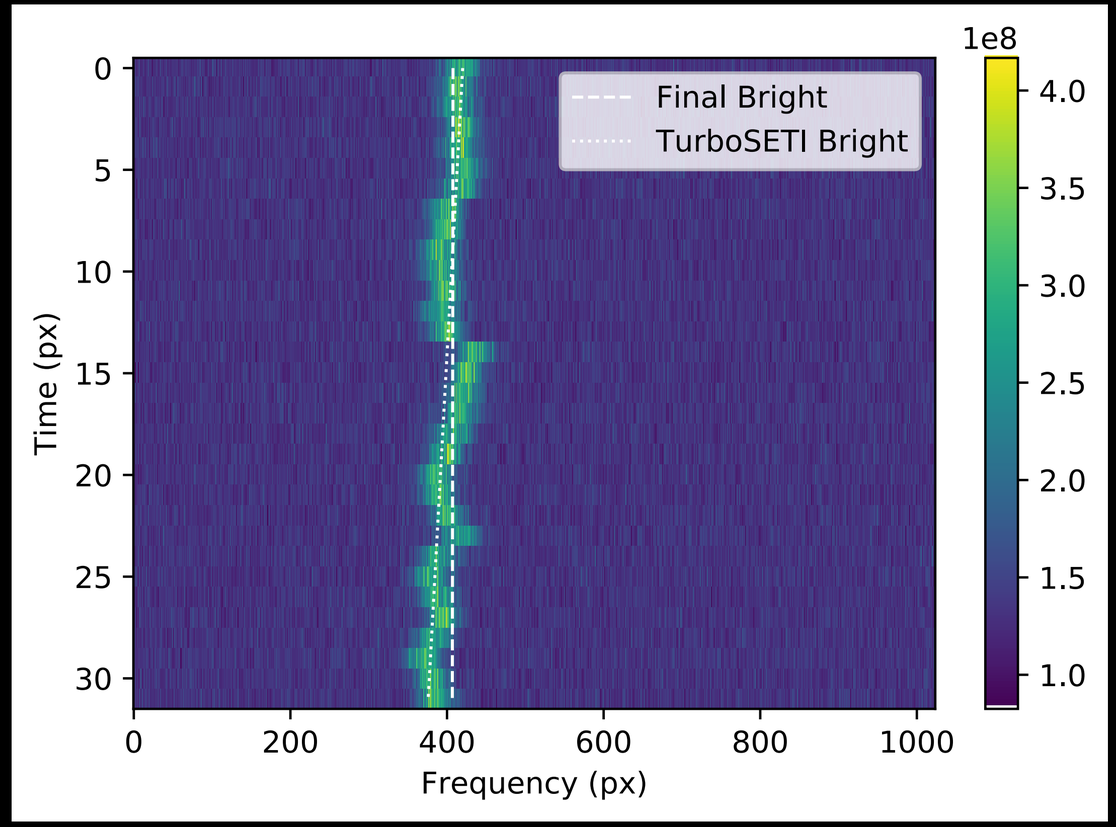
Predicted locations



Brzycki et al. 2020,

Takeaways

- Less accurate than deDoppler methods, but generally 20-40x faster
- Trained on ideal signals but still relatively robust
- For production use, would need to extend to variable number of signals

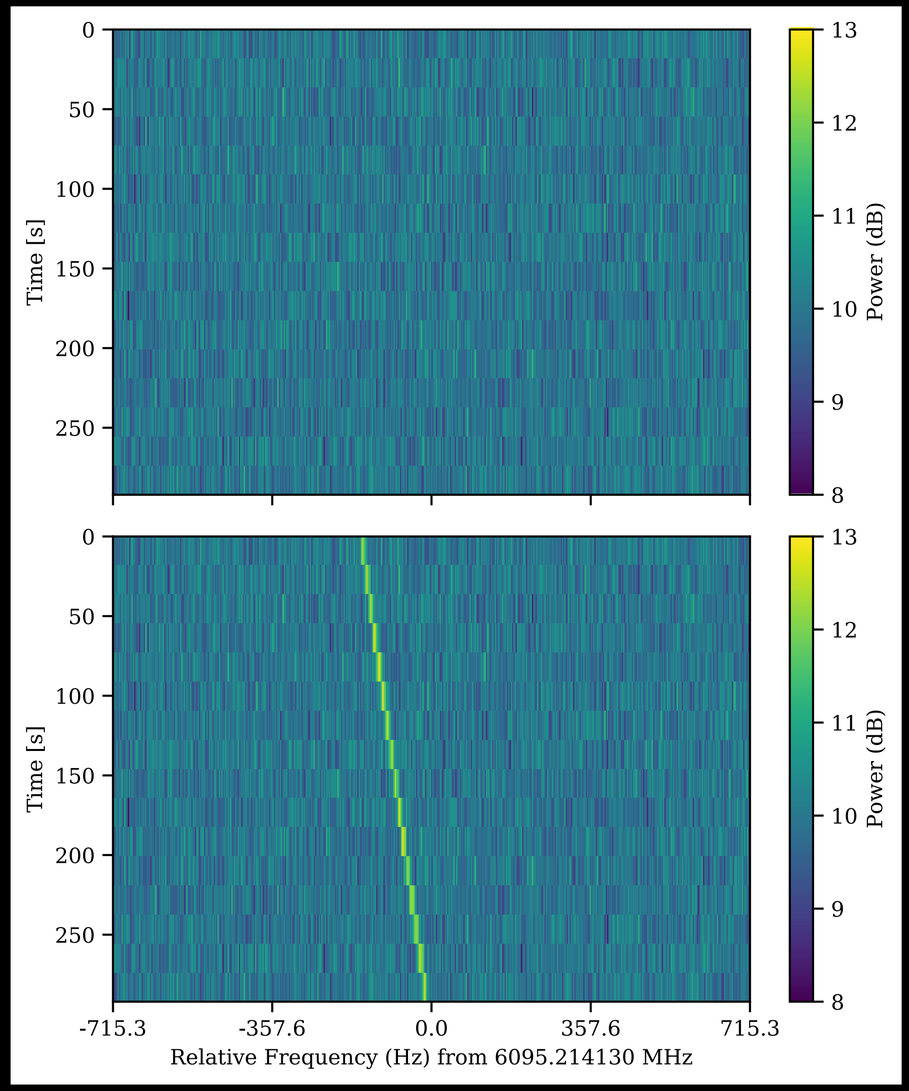


C-band RFI signal, with ML prediction dashed and TurboSETI localization dotted.

Brzycki et al. 2020,

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

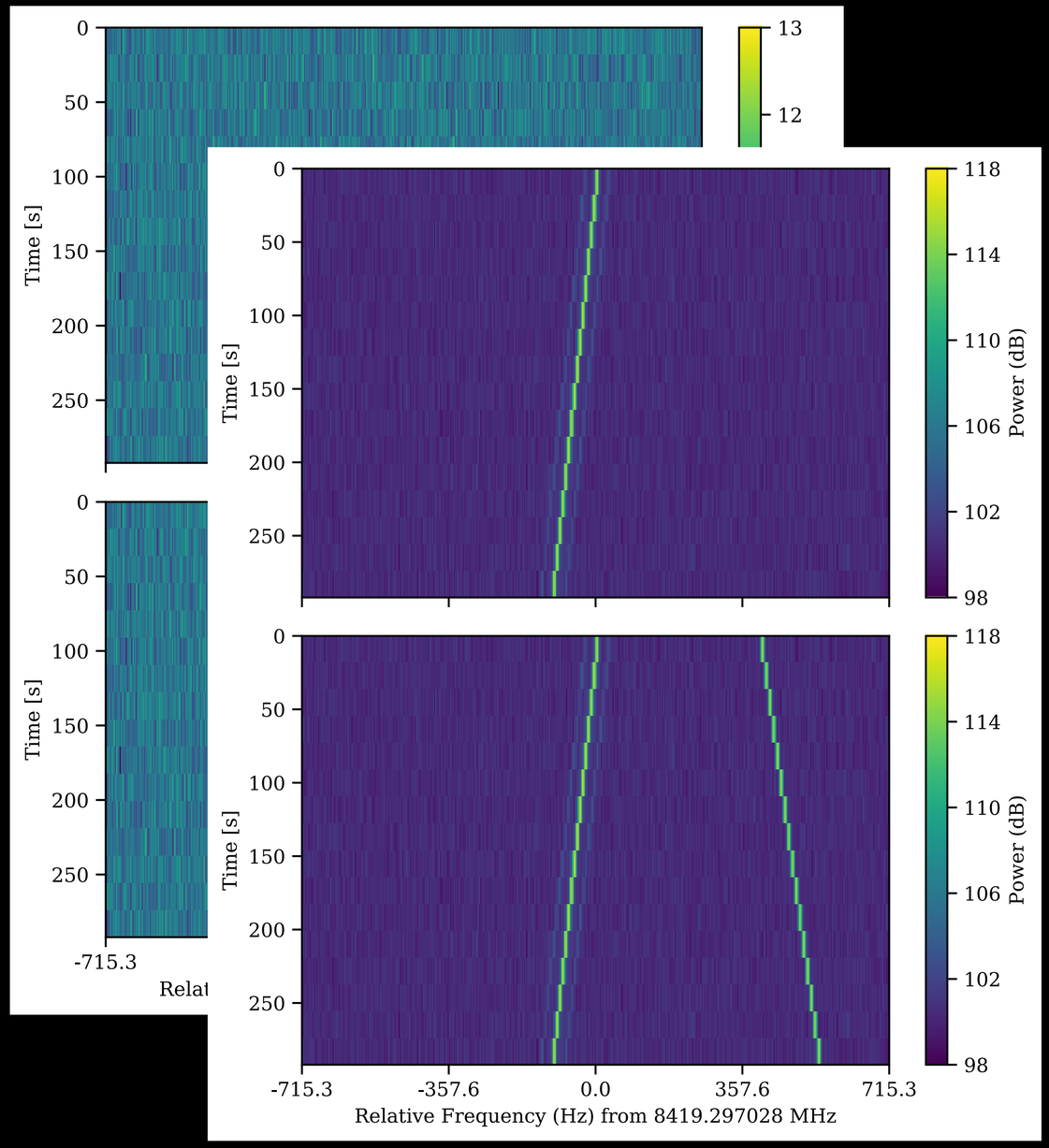
Setigen

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

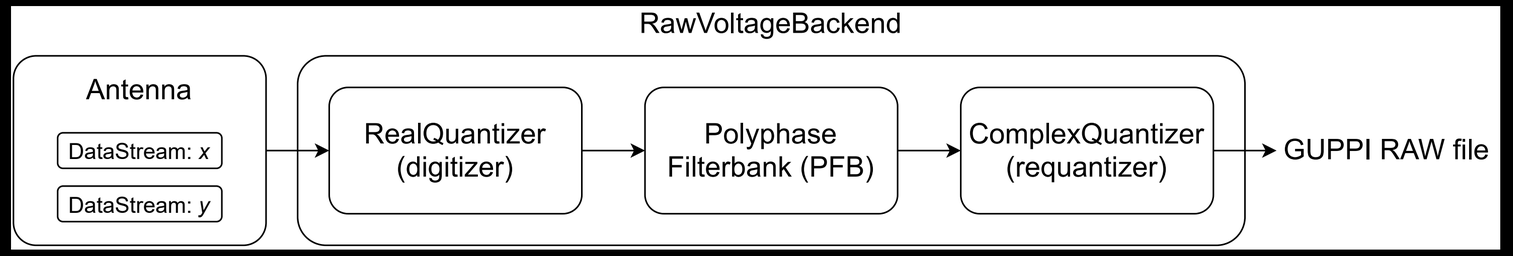
setigen Public

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

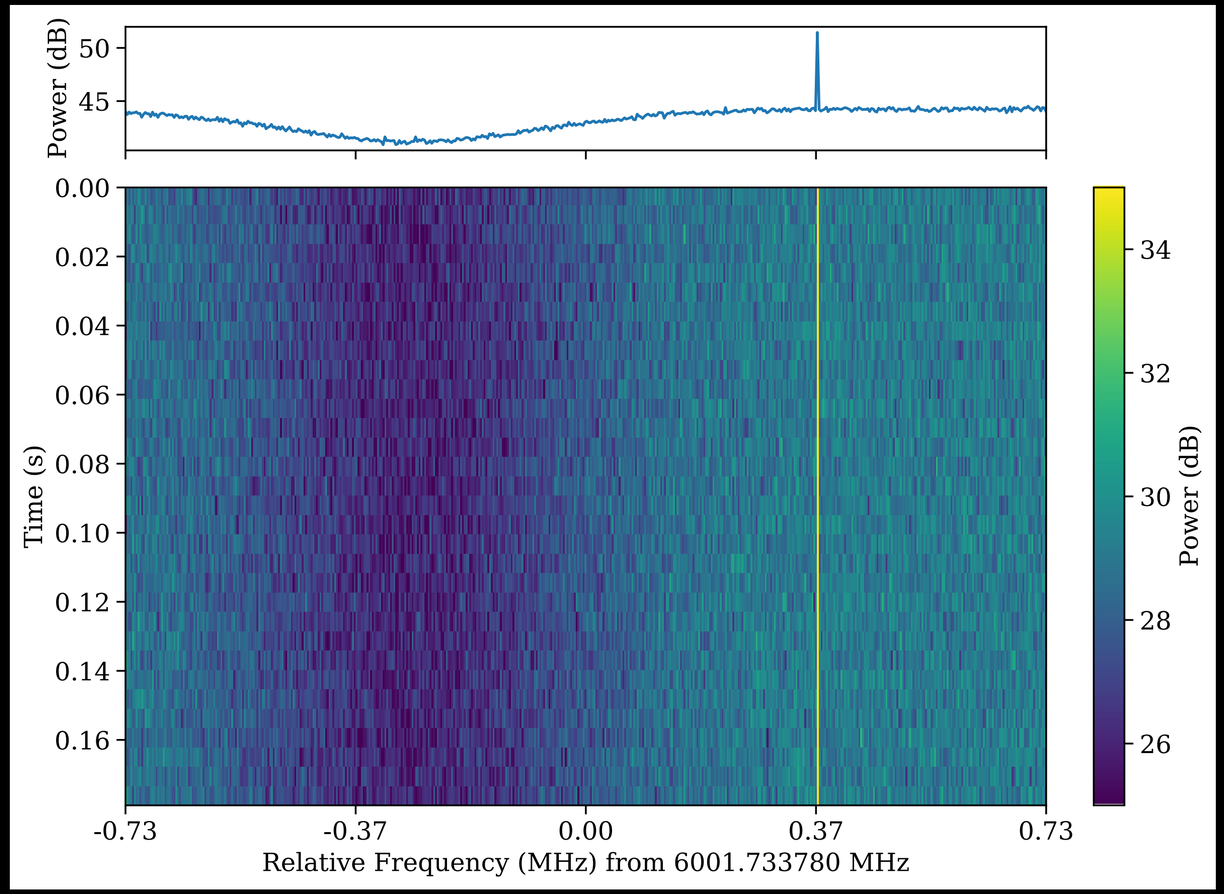
Jupyter Notebook ☆ 18 10



Brzycki et al. 2022, AJ



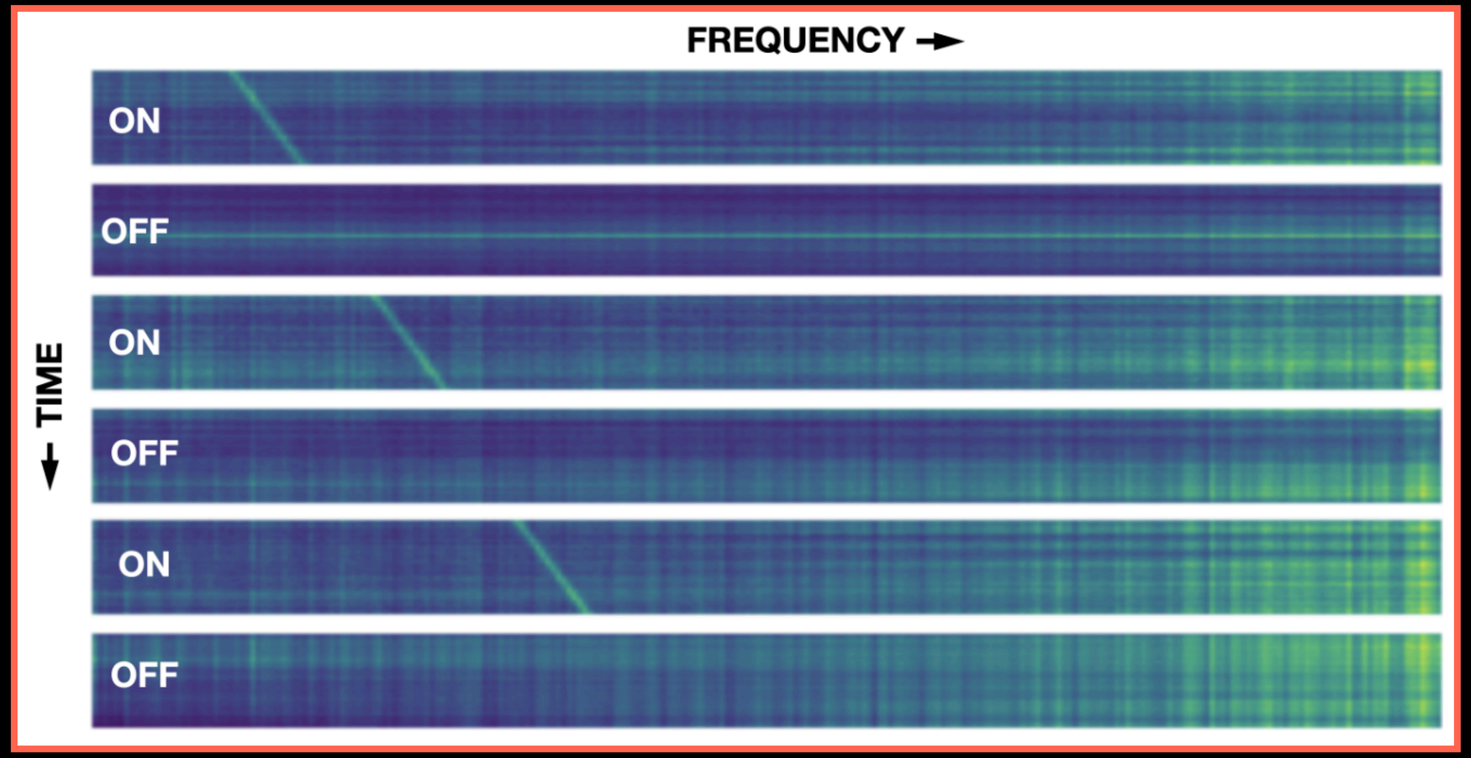
- **Synthetic complex voltage data**
- **Simple models of backend components, such as a polyphase filterbank**



Brzycki et al. 2022, AJ

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

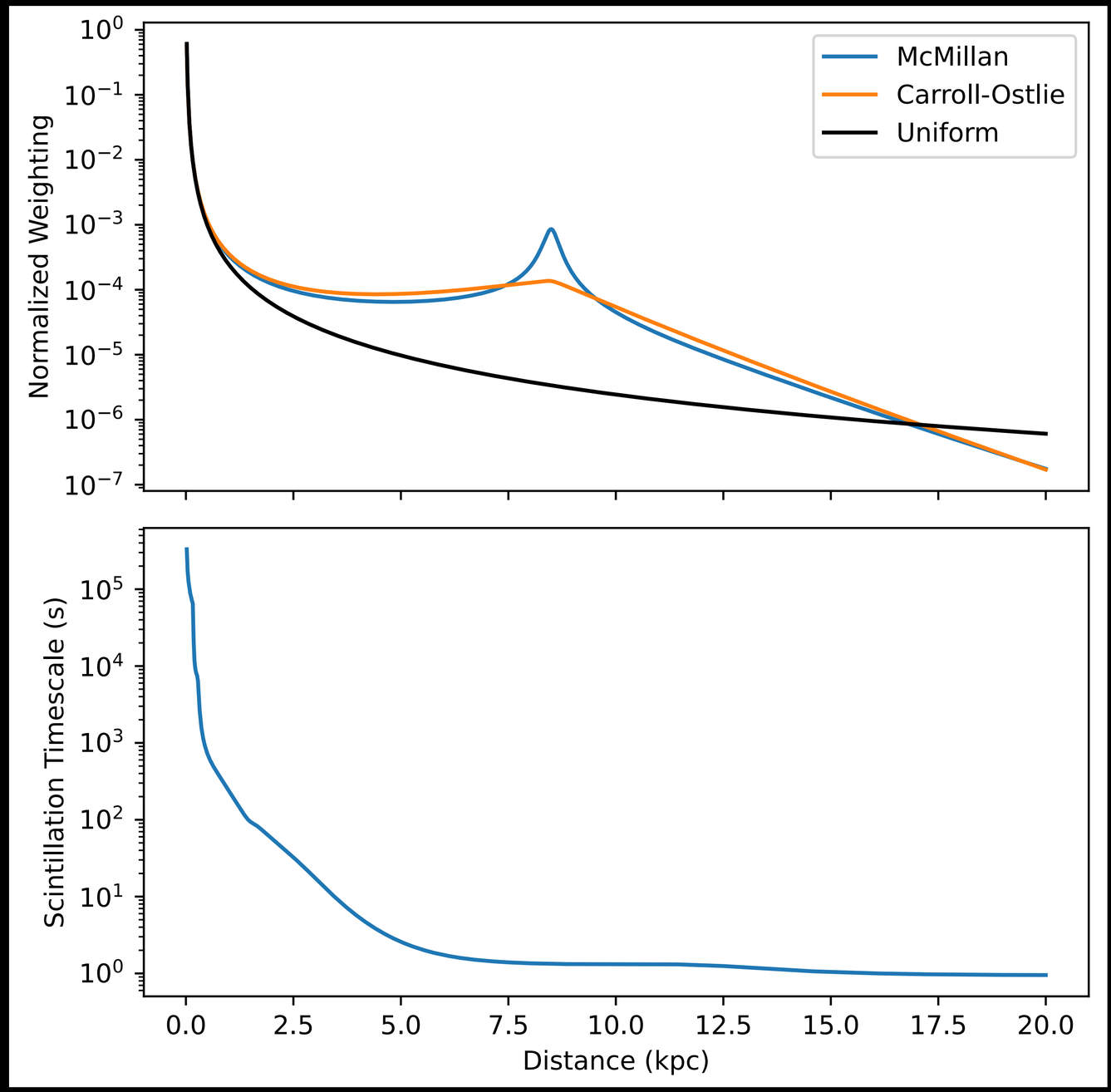


Breakthrough Listen x Kaggle

Density-based sampling

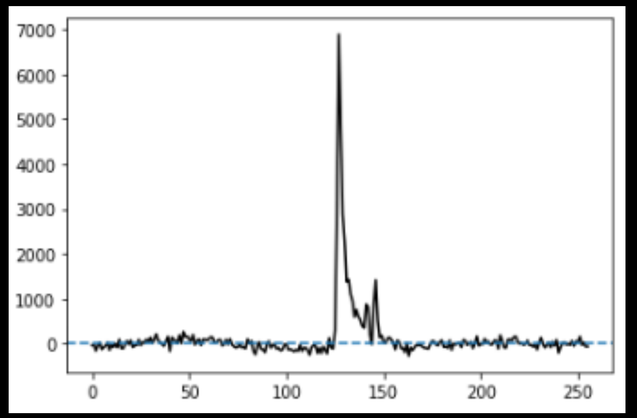
Modulating by the inverse square-law for detectability:

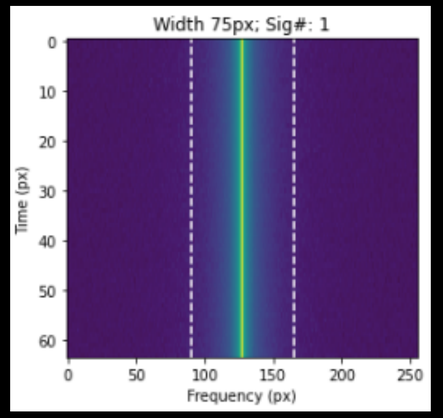
Depends on the assumptions made about transmission power and resources.



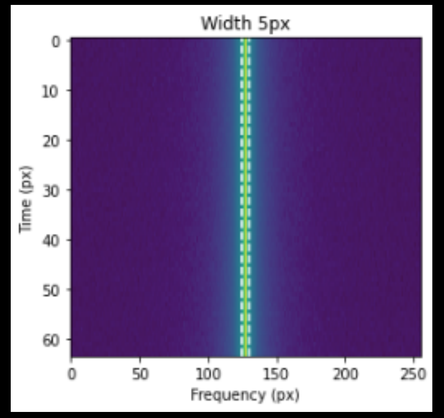
Selecting bounding boxes

- 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





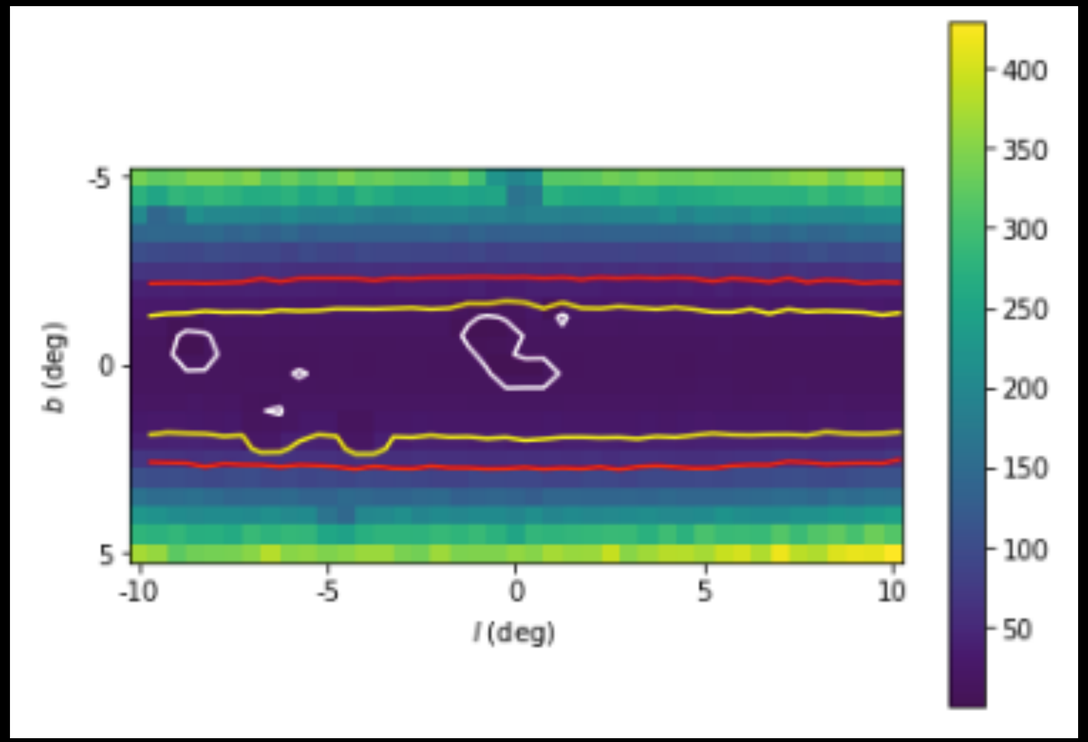
Polynomial fit



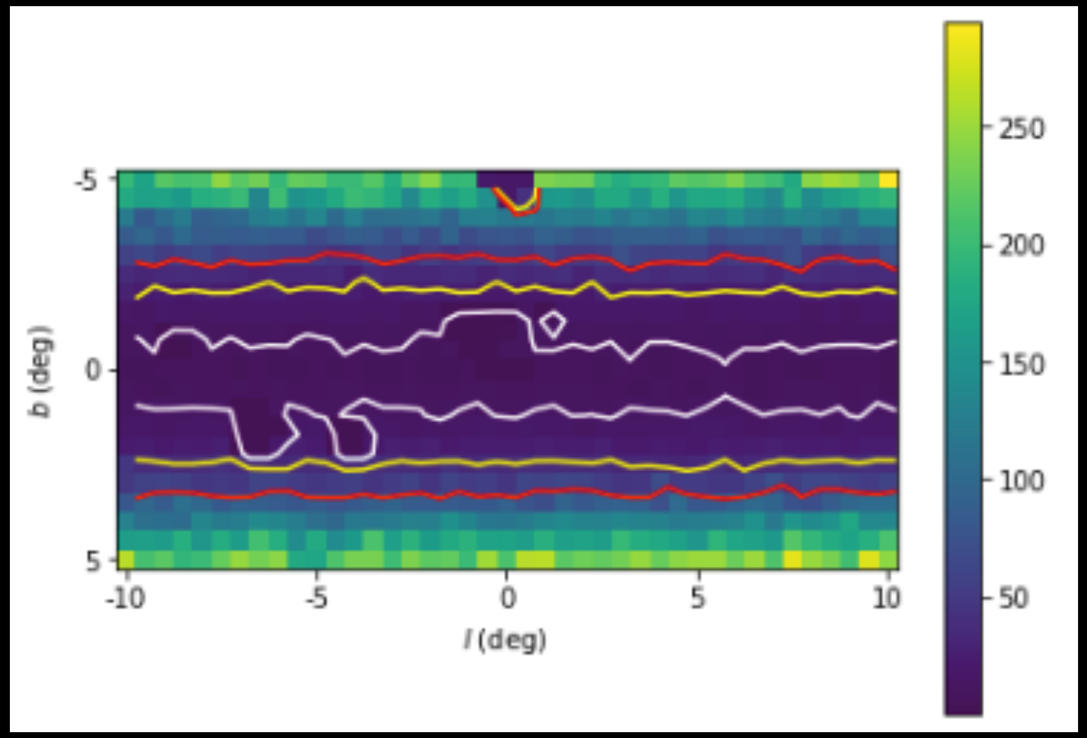
Threshold fit

Scintillation maps around the GC at C-band

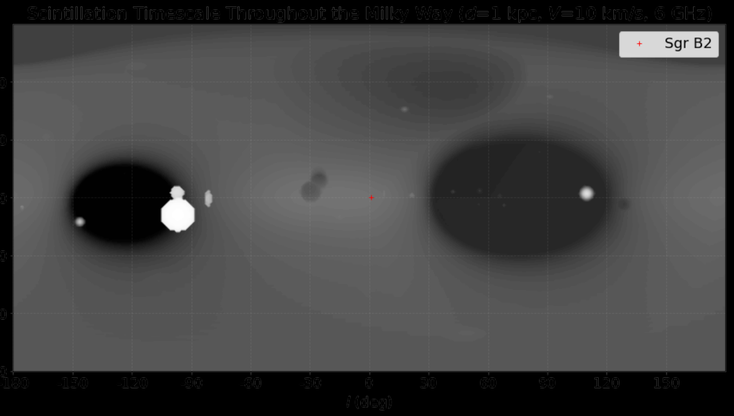
Median

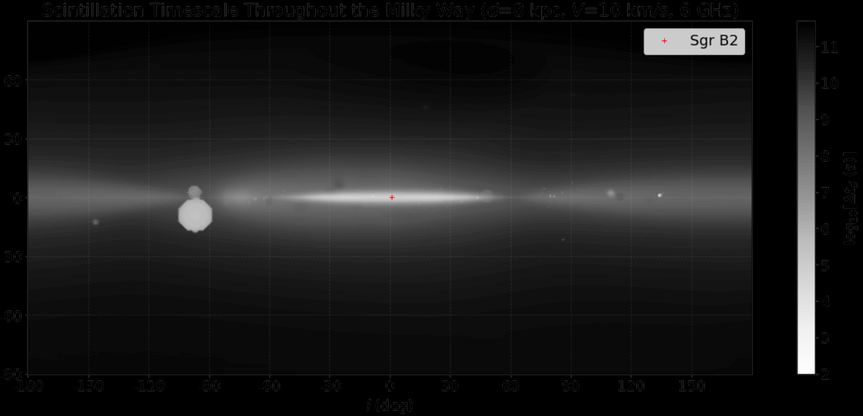


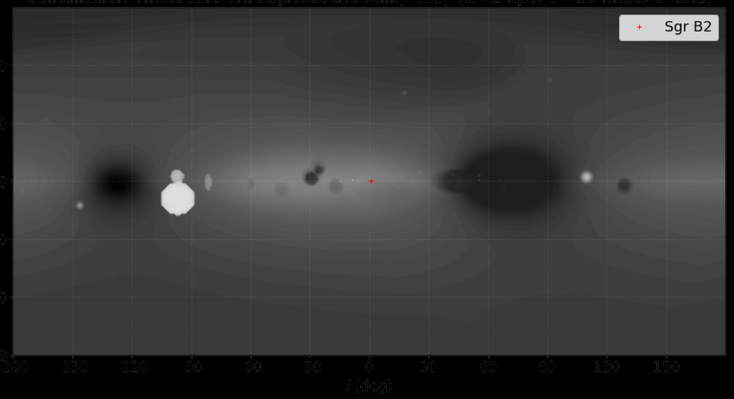
Mode

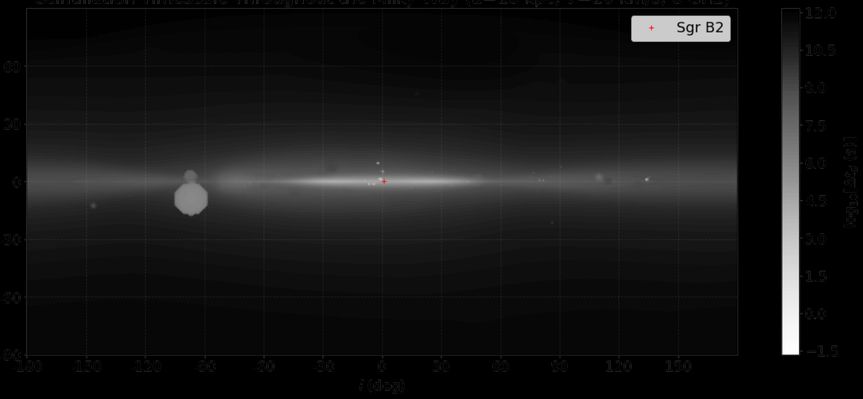


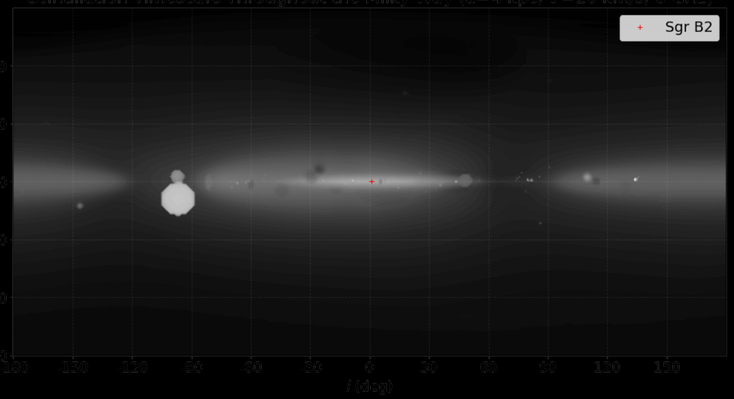
10 s, 30 s, 60 s

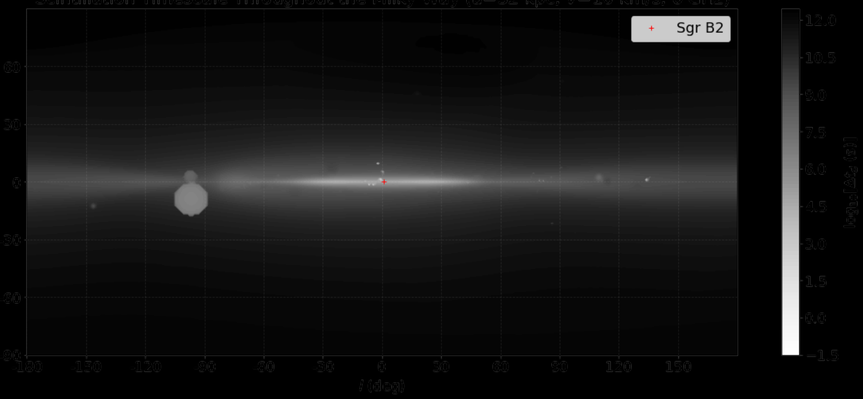

Scintillation Timescale Throughout the Milky Way (d=1 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))


Scintillation Timescale Throughout the Milky Way (d=2 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))


Scintillation Timescale Throughout the Milky Way (d=2 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))

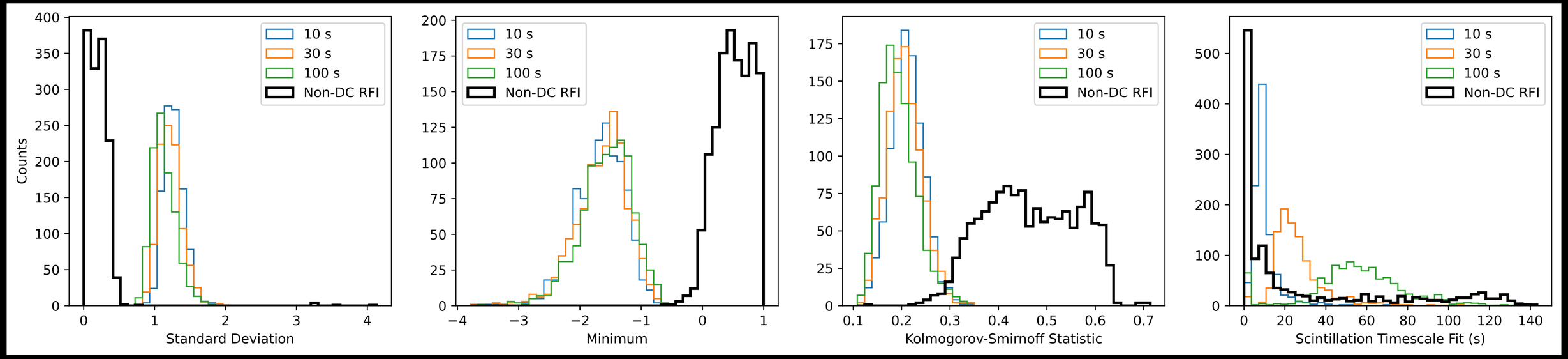

Scintillation Timescale Throughout the Milky Way (d=16 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))


Scintillation Timescale Throughout the Milky Way (d=4 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))


Scintillation Timescale Throughout the Milky Way (d=32 kpc, V=10 km/s, 6 GHz)
Sgr B2
b (deg)
l (deg)
log(τ_sc (s))

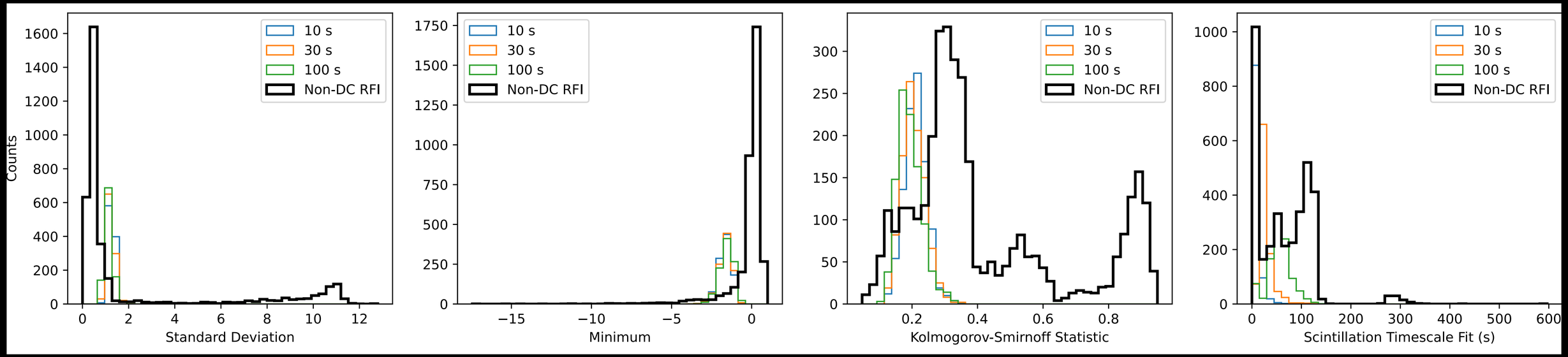
C band

S/N = 10


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

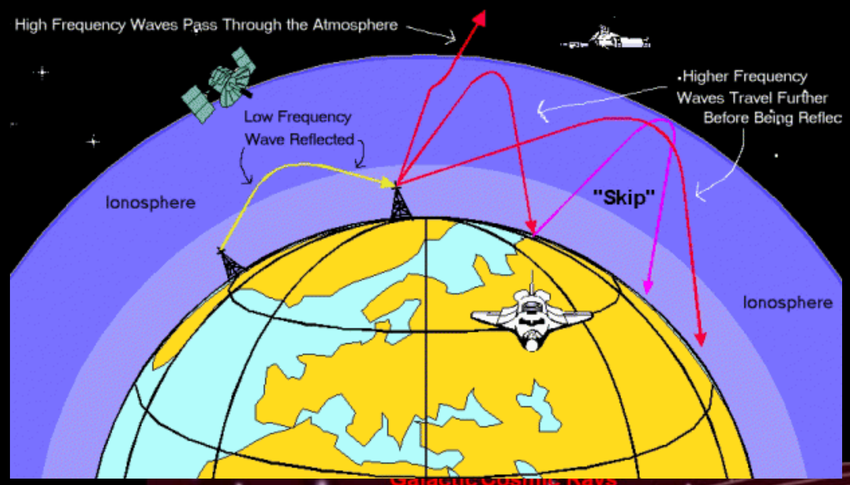
L band

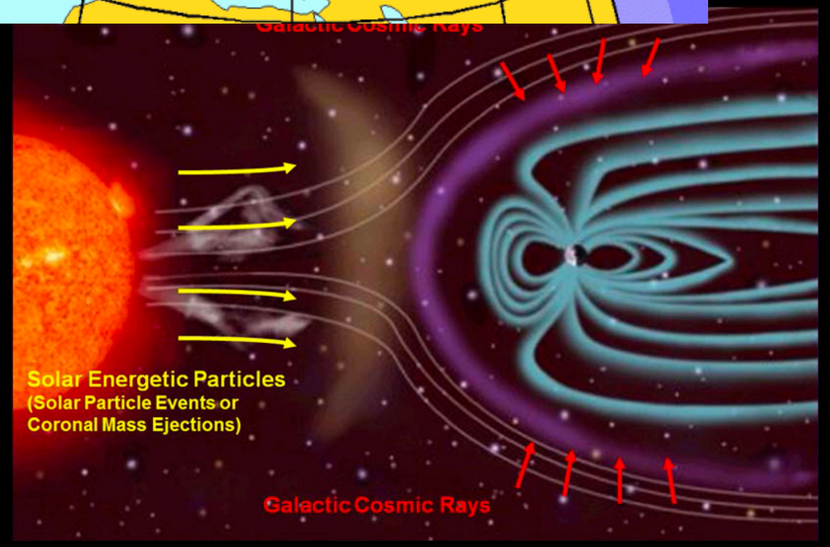
S/N = 10

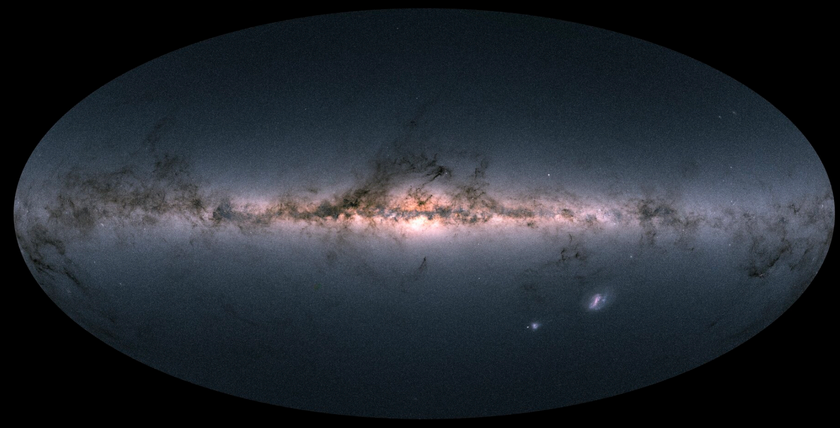

Counts
Standard Deviation
Minimum
Kolmogorov-Smirnoff Statistic
Scintillation Timescale Fit (s)
10 s
30 s
100 s
Non-DC RFI

Scattering intensity

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

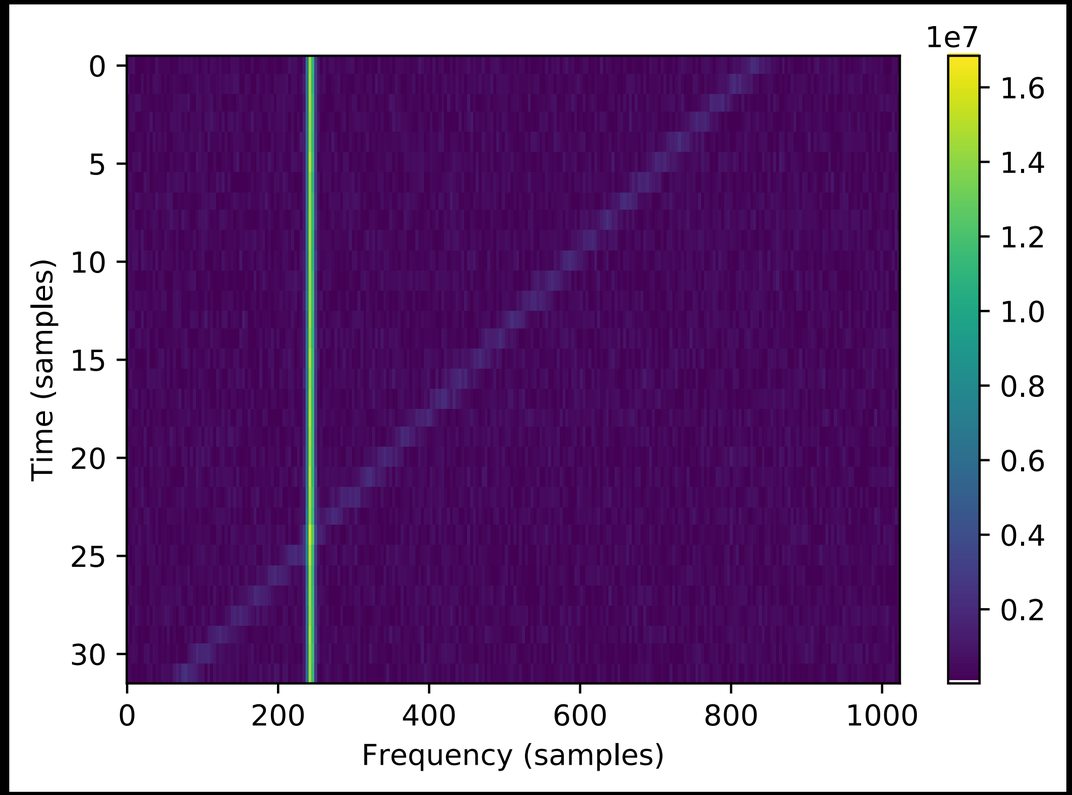






Narrow-band signal localization (Brzycki et al. 2020)

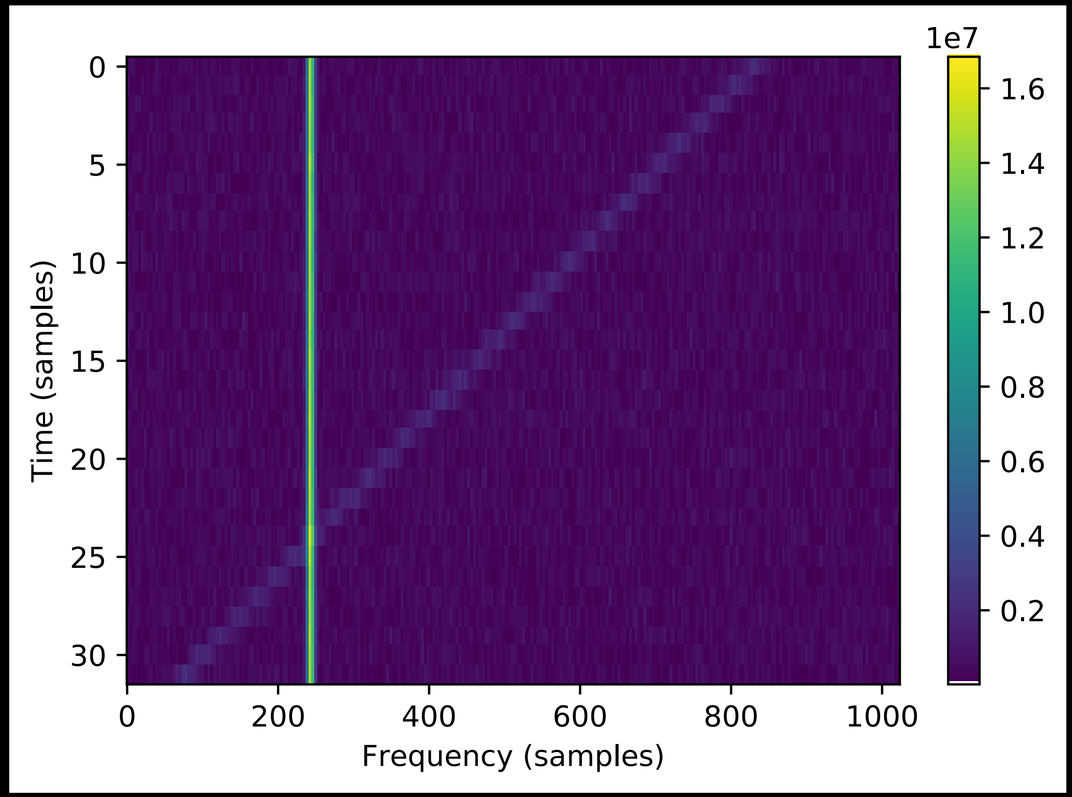
- With a means of simulating observational data, we can produce frames that would be hard to find “organically” using TurboSETI
- Importantly, we can generate lots of relevant labeled synthetic data, and train a CNN to find these signals
- Localization of narrow-band signals is a good initial ML problem because it’s a relatively simple task; predict 2 numbers per signal



Example of a frame with 2 synthetic signals, at 25 and 15 dB.

Narrow-band signal localization (Brzycki et al. 2020)

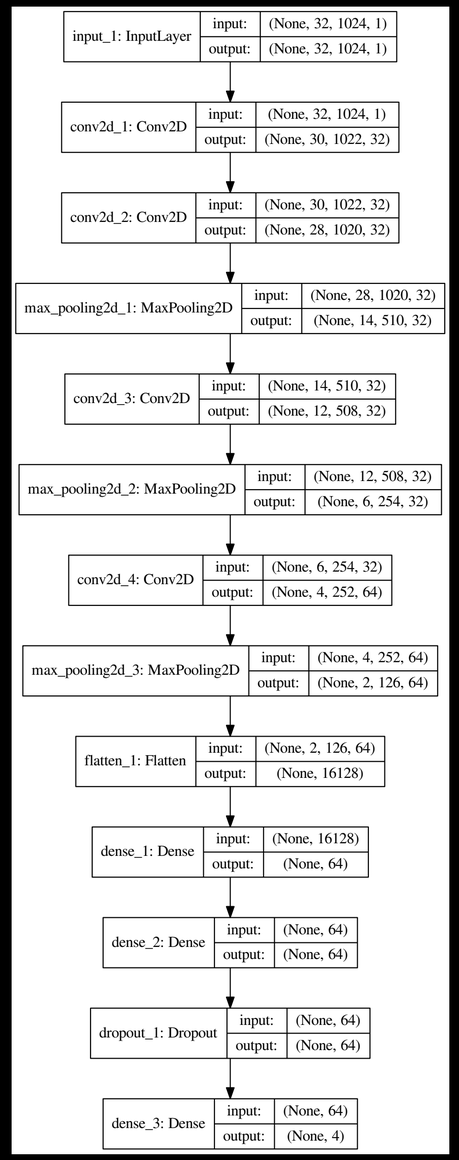
- Created two main datasets, both with 120,000 training samples and 24,000 test samples of size 32x1024 px
  - One signal, at 0, 5, ..., 25 dB with random drift rate
  - Two signals, one at 0, 5, ..., 25 dB with random drift rate, and the other at 25 dB with 0 drift rate (meant to simulate “bright” RFI)
- The one signal dataset allows for direct comparison with TurboSETI; the two signal dataset tests the effectiveness of localizing multiple signals simultaneously

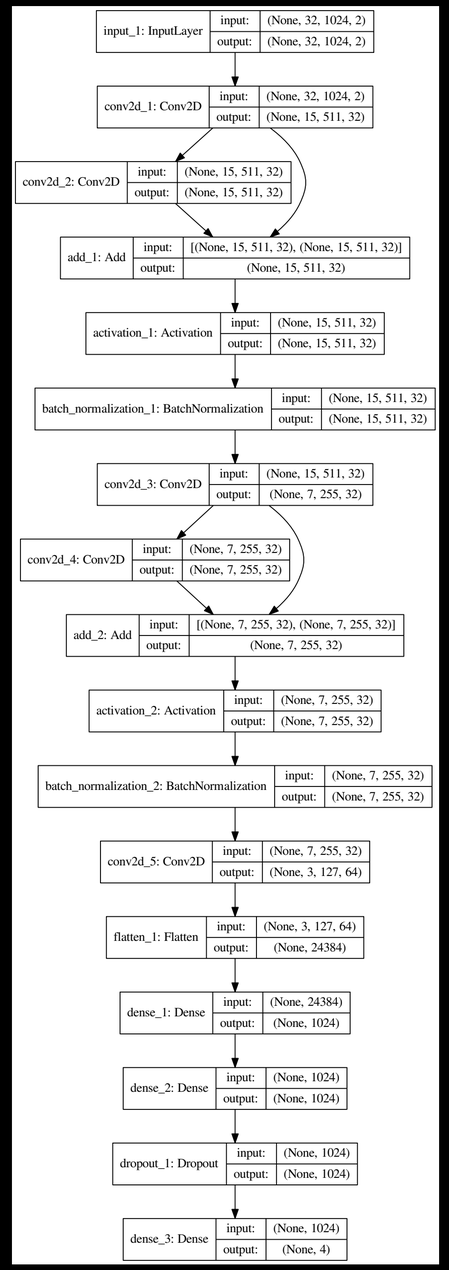


Example of a frame with 2 synthetic signals.

Model architectures

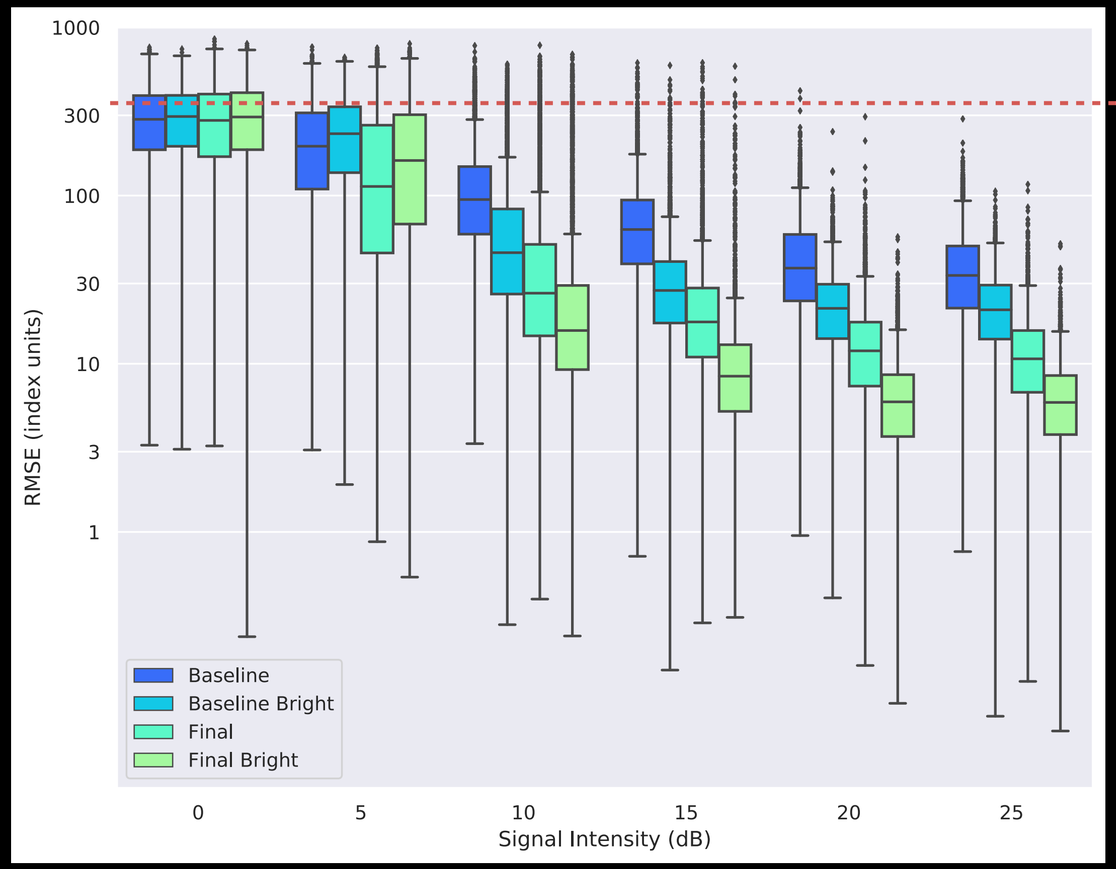
- Used convolutional neural networks, especially suited for image input data
- Created a “baseline” and a “final” model, to compare performance:
  - Baseline model uses convolutional layers, max pooling, and fully connected layers
  - Final model includes residual connections, stride 2 convolutions instead of max pooling, and batch normalization
- In addition to training these models over all input training data, we did alternate training over only 10 - 25 dB signal frames, labeling these as “bright” models



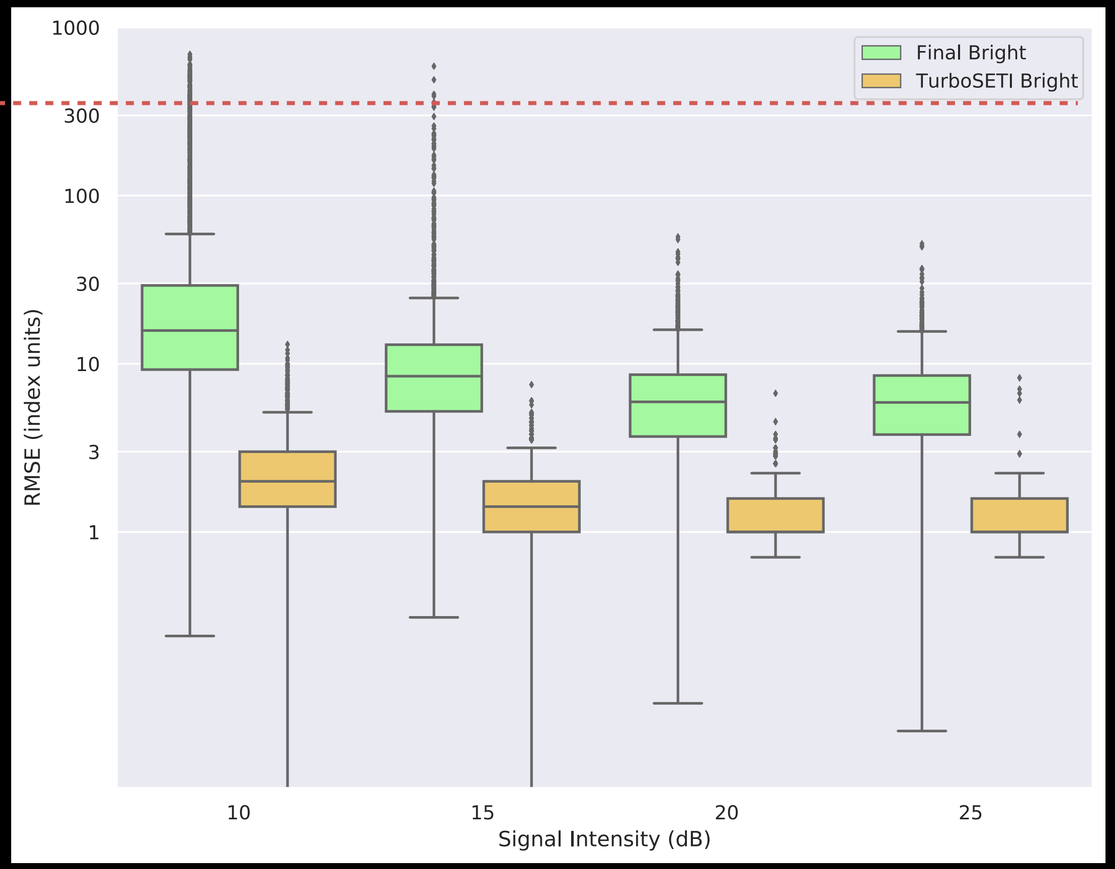


$$\text{RMSE (index units)} = 1024 \times \sqrt{\frac{1}{n}\sum_{i}^{n}(y_i - \hat{y}_i)^2}$$

One signal results on test data



Root mean squared error (in pixels) across different models

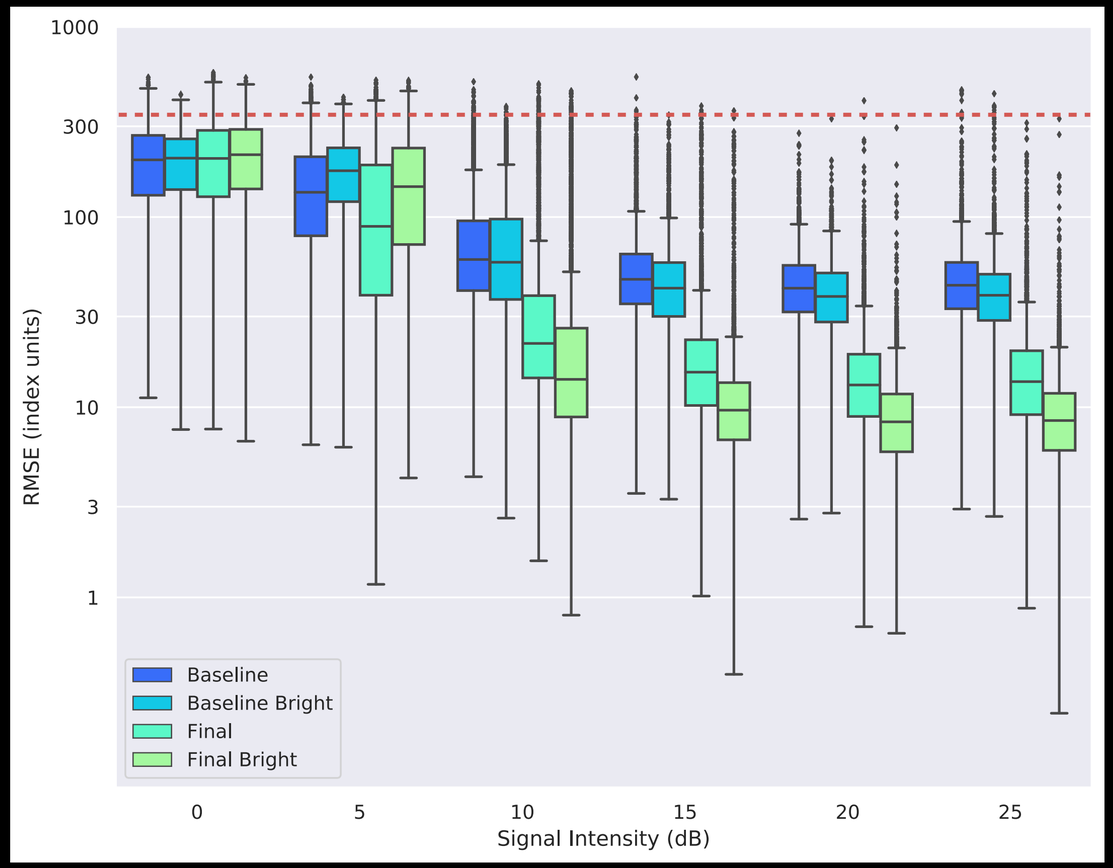


Root mean squared error (in pixels) for best ML model vs. TurboSETI. Only calculated for SNR > 10.

$$\text{RMSE (index units)} = 1024 \times \sqrt{\frac{1}{n}\sum_{i}^{n}(y_i - \hat{y}_i)^2}$$

Two signal results on test data

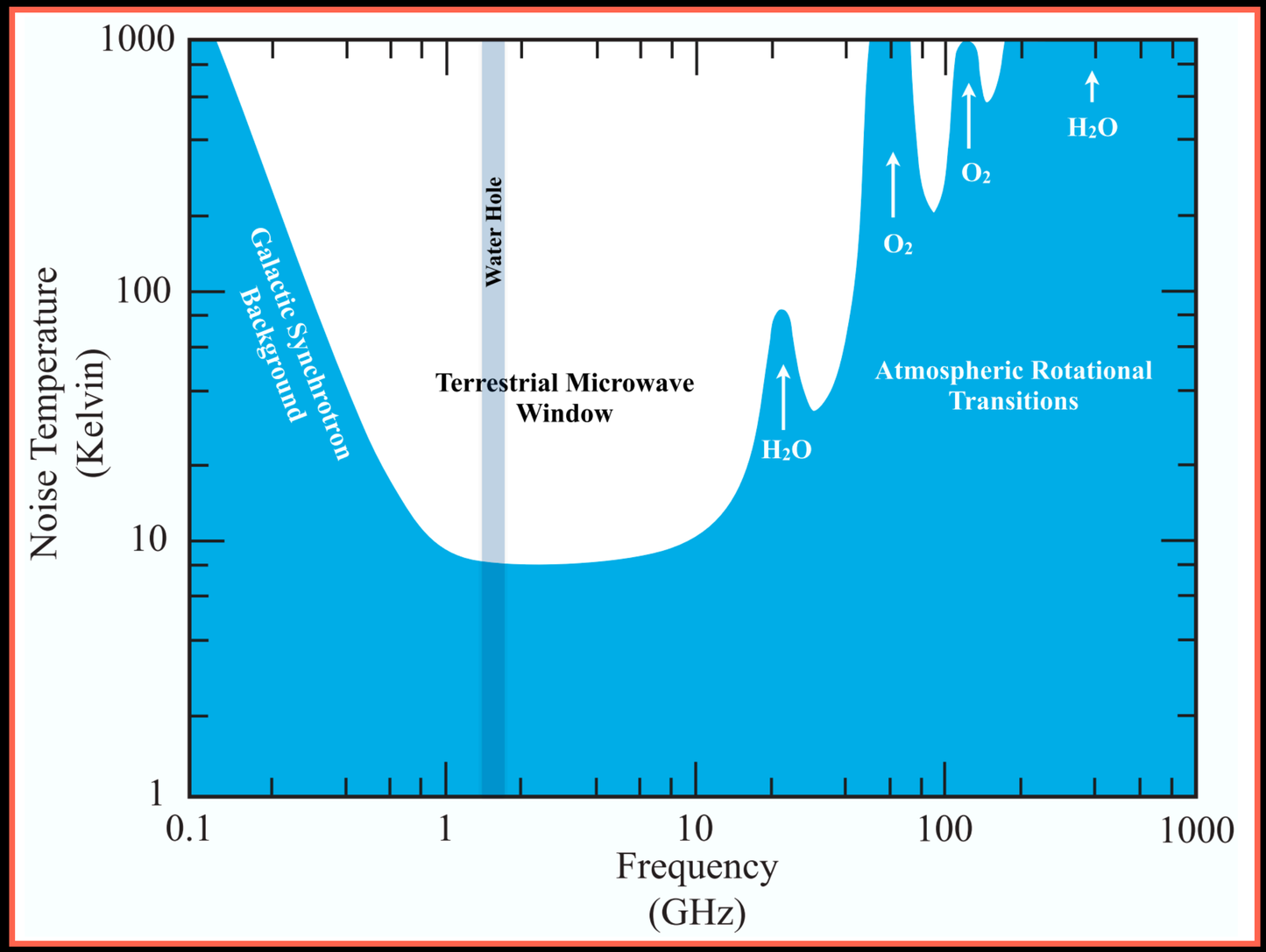
- Performance over two signal case is slightly worse than in the one signal case
- Even though we used ideal synthetic signals, our best models failed to localize to extremely high precision
- Nevertheless, our two signal model architectures were able to localize the dimmer signal better than random, so these results are still encouraging



Root mean squared error across different signal intensities, in pixels, for various neural network architectures in the 2 signal case.

Why radio?

- Low energy to produce
- Low attenuation
- Produced by technology!



Siemion et al.

Prior SETI research on scintillation

- Cordes & Lazio 1991 recommended multi-epoch observing campaigns
- Many studies acknowledge the possibility of scintillation
- Generally, SETI techniques aren't sensitive to detailed morphology
- Stochastic effects are hard to describe

INTERSTELLAR SCATTERING EFFECTS ON THE DETECTION OF NARROW-BAND SIGNALS

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