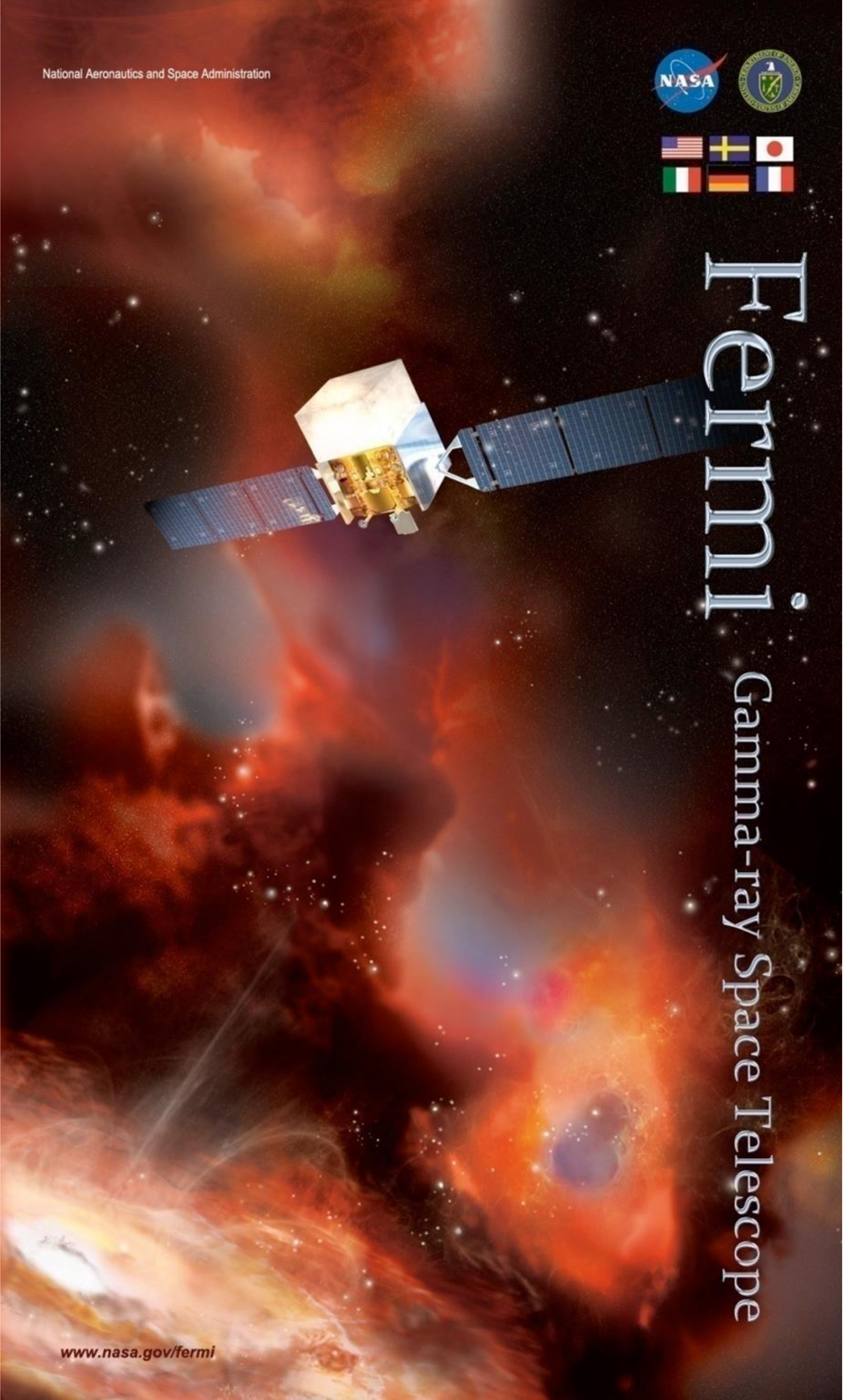


Gamma-ray Pulsars are Mostly Clean Machines*

*with apologies to Andrey Timokhin

Matthew Kerr
US Naval Research Laboratory

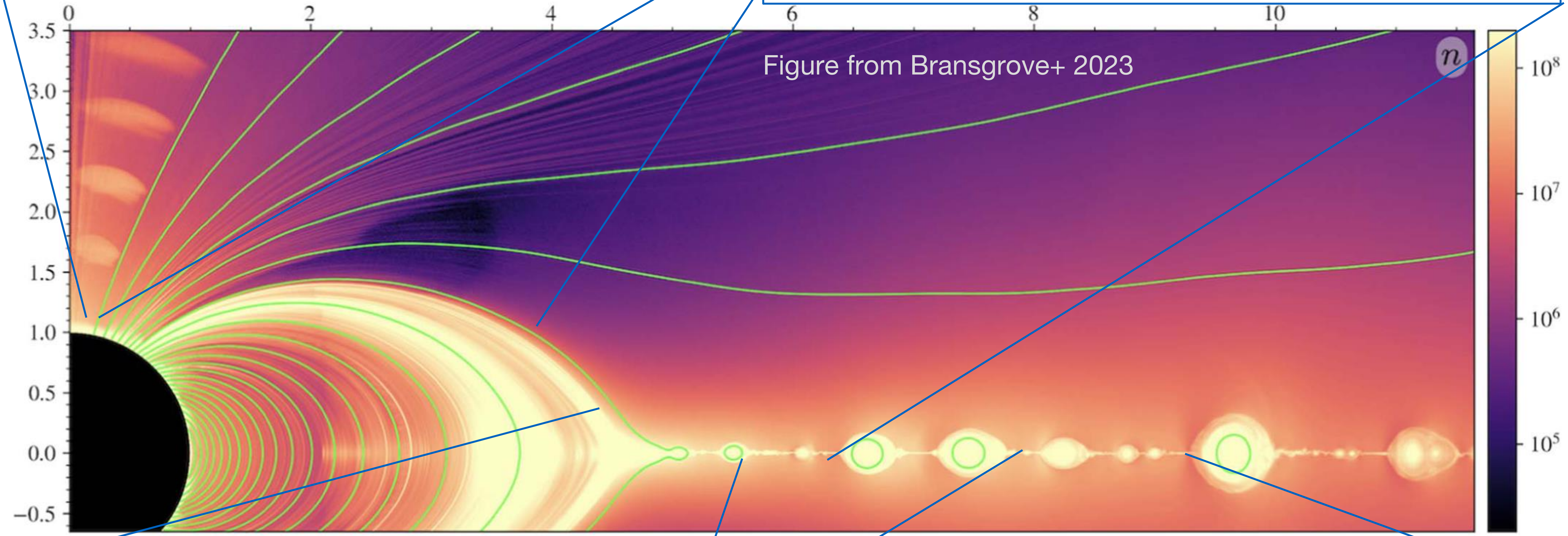
on behalf of the Fermi-LAT Collaboration

9th September, 2024
11th Fermi Symposium

Pulsar Models Are Now Wildly Successful

- Sparking on field lines with super-Goldreich Julian current forms pairs (Beloborodov 2008, Timokhin & Arons 2013)
- Resulting EM modes promising for inference of radio! (e.g. Philippov+ 2020, Bransgrove+ 2023, Benáček+2024)

- Structure of the magnetosphere features a separatrix and current sheet
- determined in force-free case (Contopoulos+ 1999, Spitkovsky 2006);
- refined and verified with dissipitative / PIC simulations. (e.g. Kalapotharakos+ 2012, Philippov & Spitkovsky 2014…)



- Gamma-ray light curves consistent with beaming along magnetic field lines at separatrix (Bai & Spitkovsky 2010, Kalapotharakos+2014, Cerutti+2016)

- Dissipation of 1-10% of Poynting flux via reconnection and efficient acceleration agrees with measured Fermi luminosities and spectra (e.g. Hakobyan+ 2023, Soudais+2024)

A general prediction of the models is plenty of pairs produced above the polar cap and in the current sheet: the pulsar is a clean machine!

But: Pulsars Don't Seem to Have Such a Steady State!

Long-term / Slow Variations: From Modest to Drastic

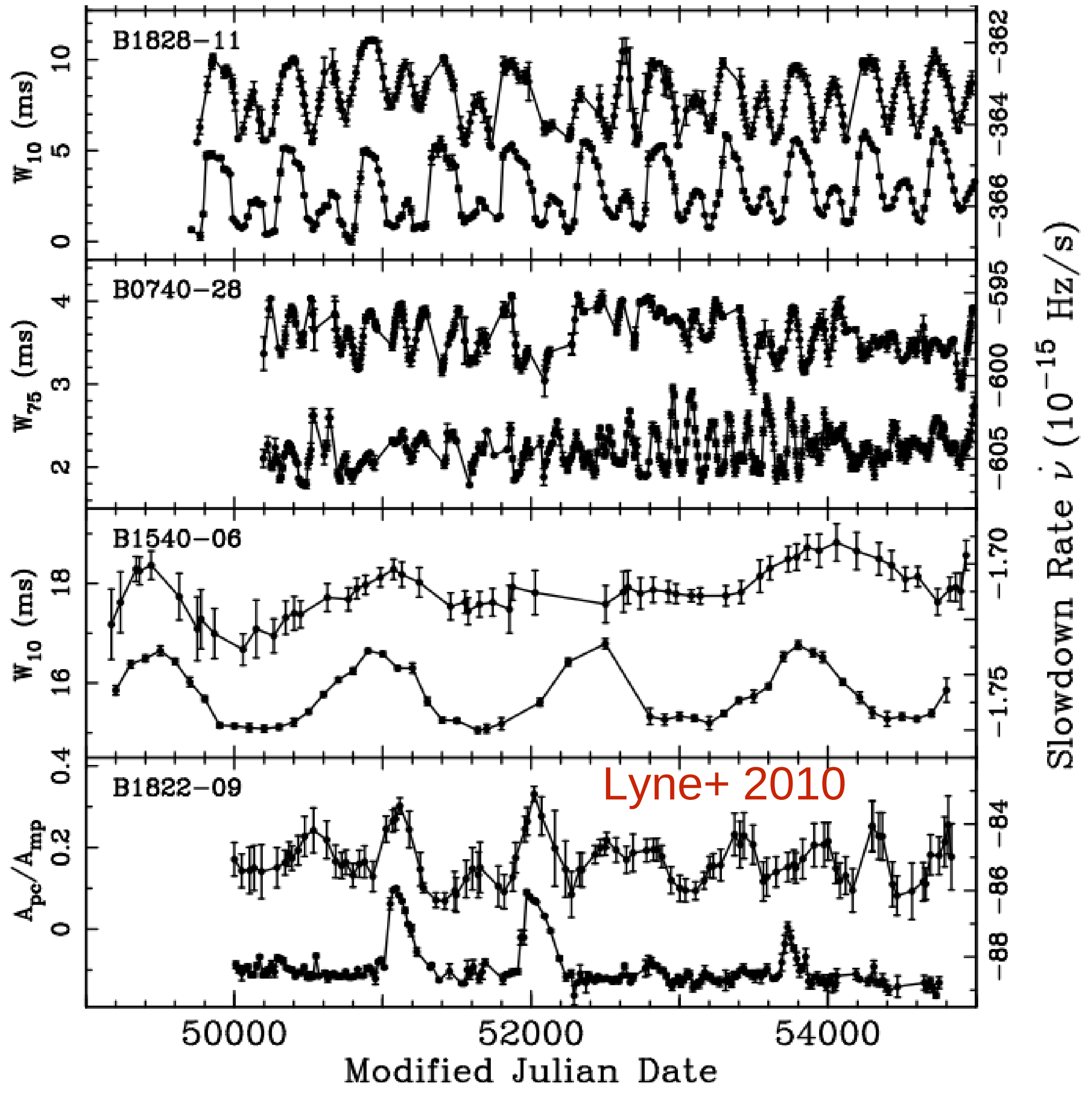
- **"State switching" pulsars** appear to oscillate between states which differ in spindown rate by about 1%, with pulse profiles that change too.

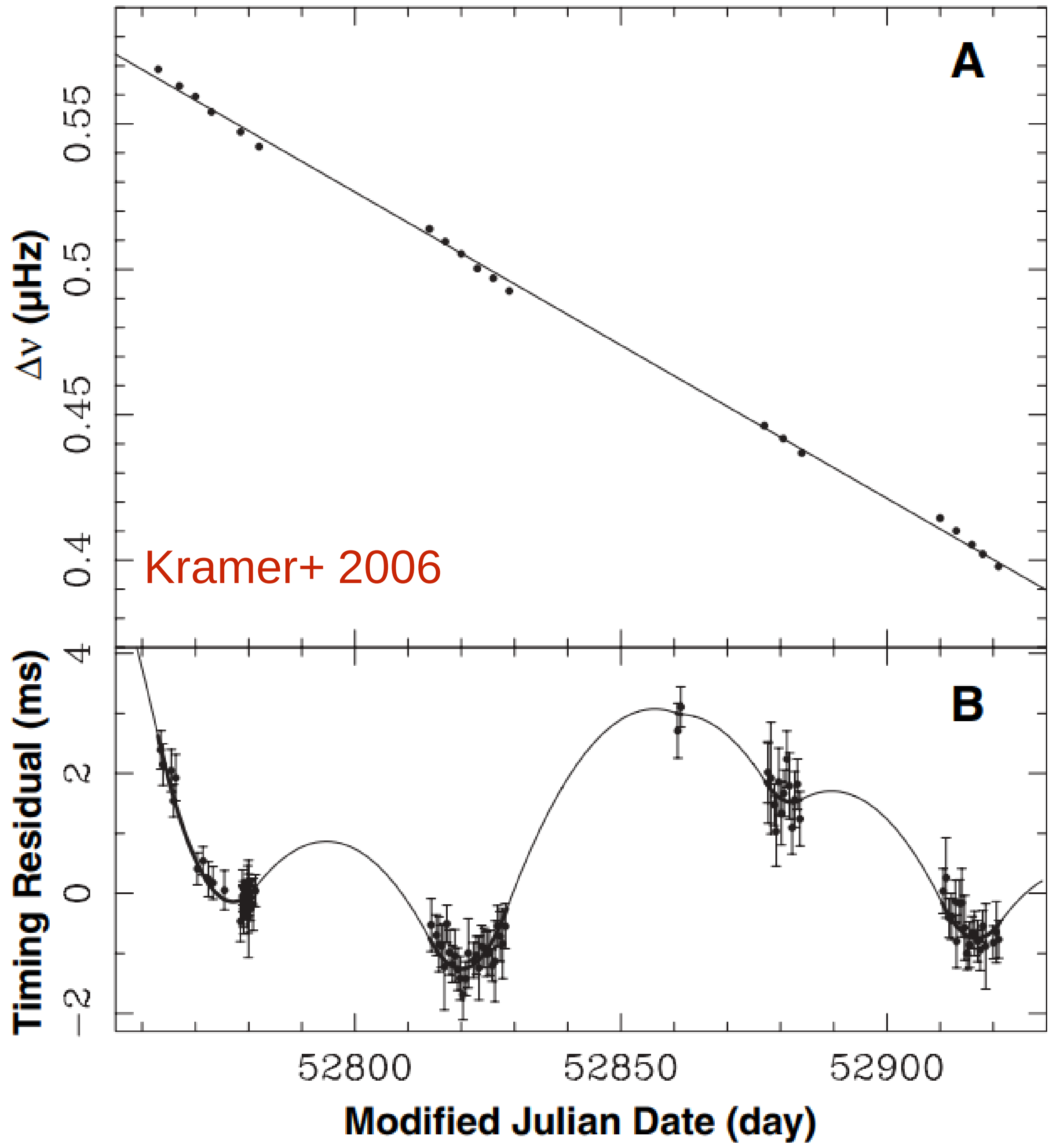
- **"Intermittent" pulsars** appear to turn off entirely for weeks to months at a time. The spindown rate when the radio pulse is gone is lower by 50—100%, consistent with transition from pair-filled magnetosphere to "dead" electrosphere. But these pulsars are far from the "death line"!

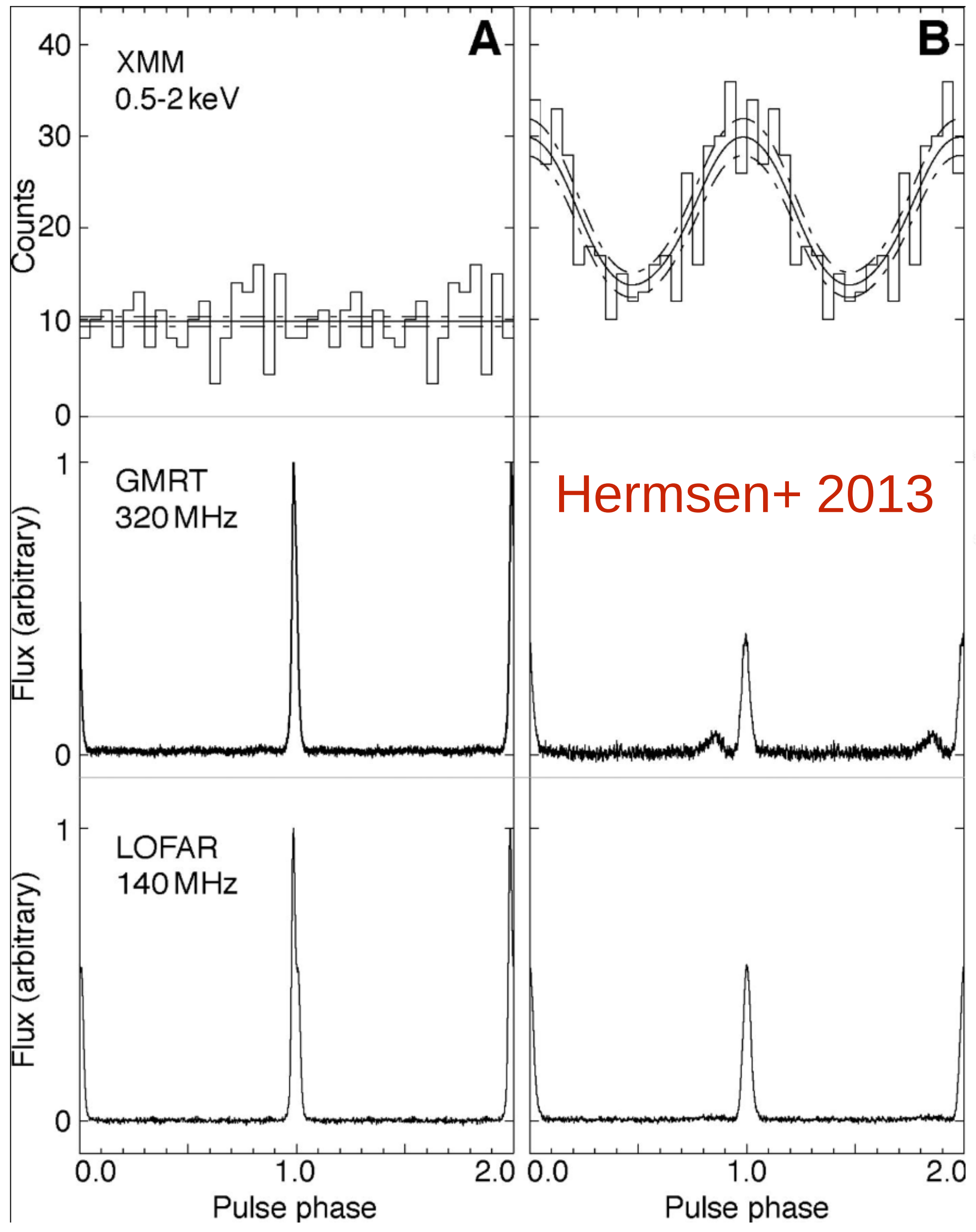
Short-term / Fast Variations: Also Modest to Drastic?

- **"Mode changing"** pulsars oscilltate between different pulse shapes, while **"nulling pulsars"** have a pulse which disappears. Both on time-scales of minutes to hours.

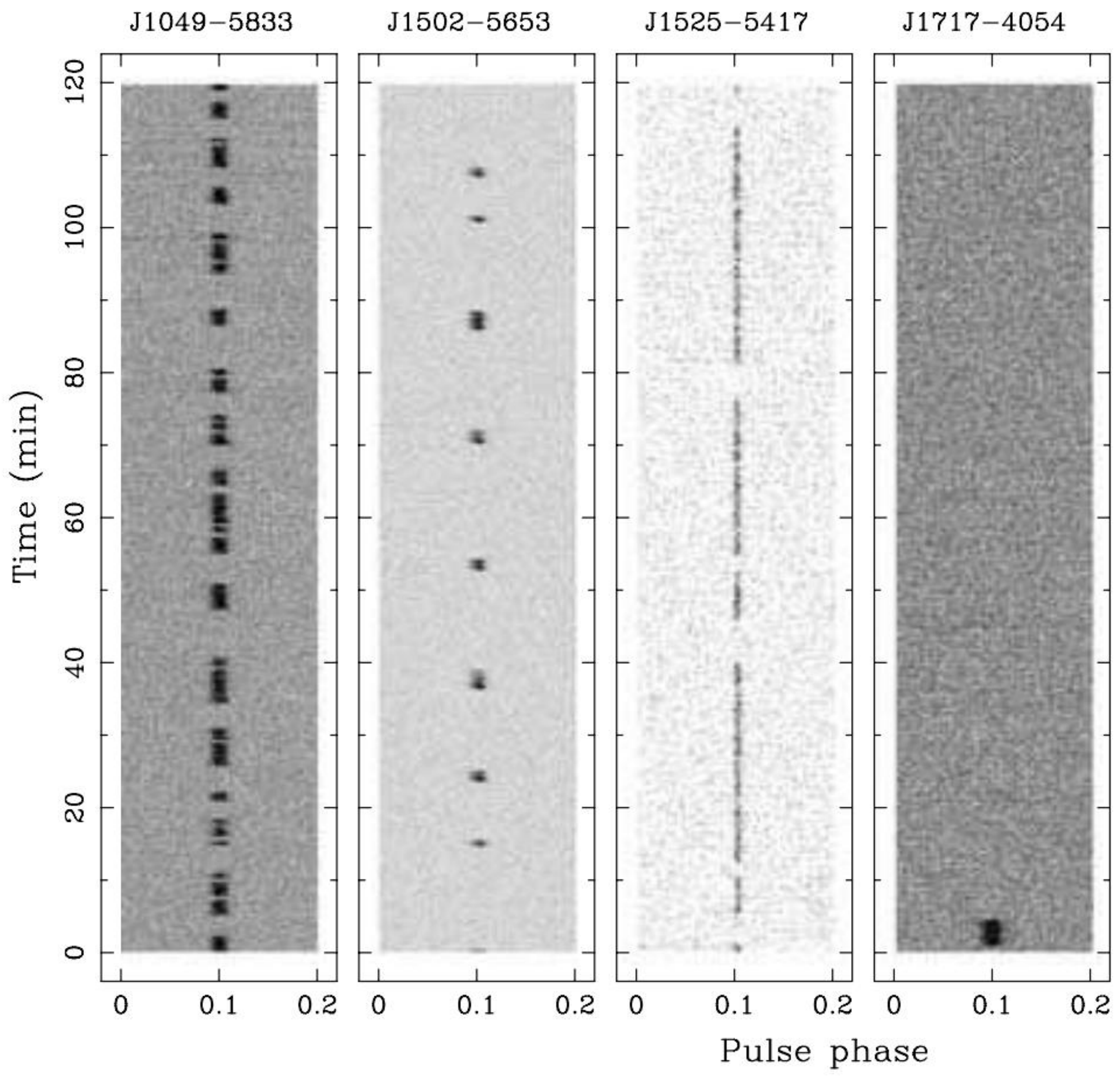
- Impossible to measure the spindown rate, but correlated X-ray variations suggest the whole magnetosphere changes. Thus, these fast variations may have the same dynamic range (pair-filled magnetosphere to dead magnetosphere) as the long-term variations.







Wang+ 2007



Key questions to understanding magnetospheric regulation: how do these variations happen, and what sets the timescale? Is the same spectrum of variations happening at short time-scales as at long time-scales?

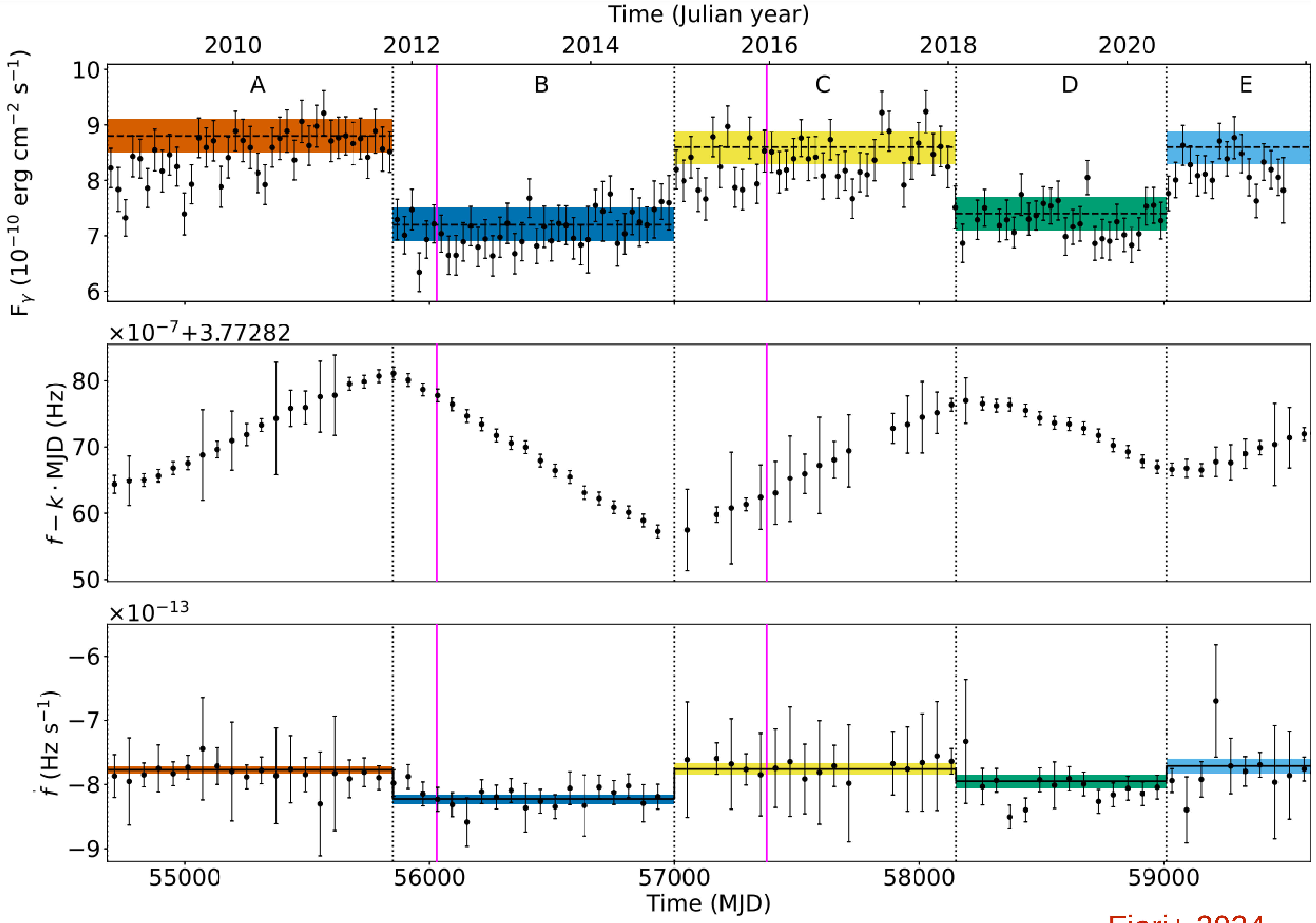
Impossible to determine with radio observations because the changes happen too rapidly to measure the spindown rate.

Gamma Ray Luminosity Tracks the Spin-Down Luminosity!

- Gamma-ray luminosity strongly tied to Poynting flux dissipated in the current sheet, and thus to total spindown rate.
  - Additional pulse shape variations if substantial variation of the open volume.

- PSR J2021+4026 exhibits very similar behavior to radio mode changers: ~10% changes in $\dot{\nu}$ correlated with ~10% changes in flux.
  - It's the only (obvious!) one!

- If Lyne et al. (2010) mechanism holds for young-ish pulsars, there should be some more pulsars with smaller levels of variation.
  - And if there are true nulls, we should see even stronger variations.



Fiori+ 2024

- Thus: look for gamma-ray flux variations on short to long timescales!
- Pick the brightest ~100 pulsars (young + MSP) for representative, stringent constraints.

Pulsar Variability Model

- Inspiration is the Lyne et al. (2010) sample and our own J2021+4026:
  - Two state system shining with flux F_b in the "bright" state and F_f in the "faint" state.
  - Mean time in each state is $T_b + W_b$ and $T_f + W_f$ respectively
  - Actual time in each state is chosen randomly: $T_b + W_b$ and $T_f + W_f$, where the W parameters are the widths of a uniform distribution.

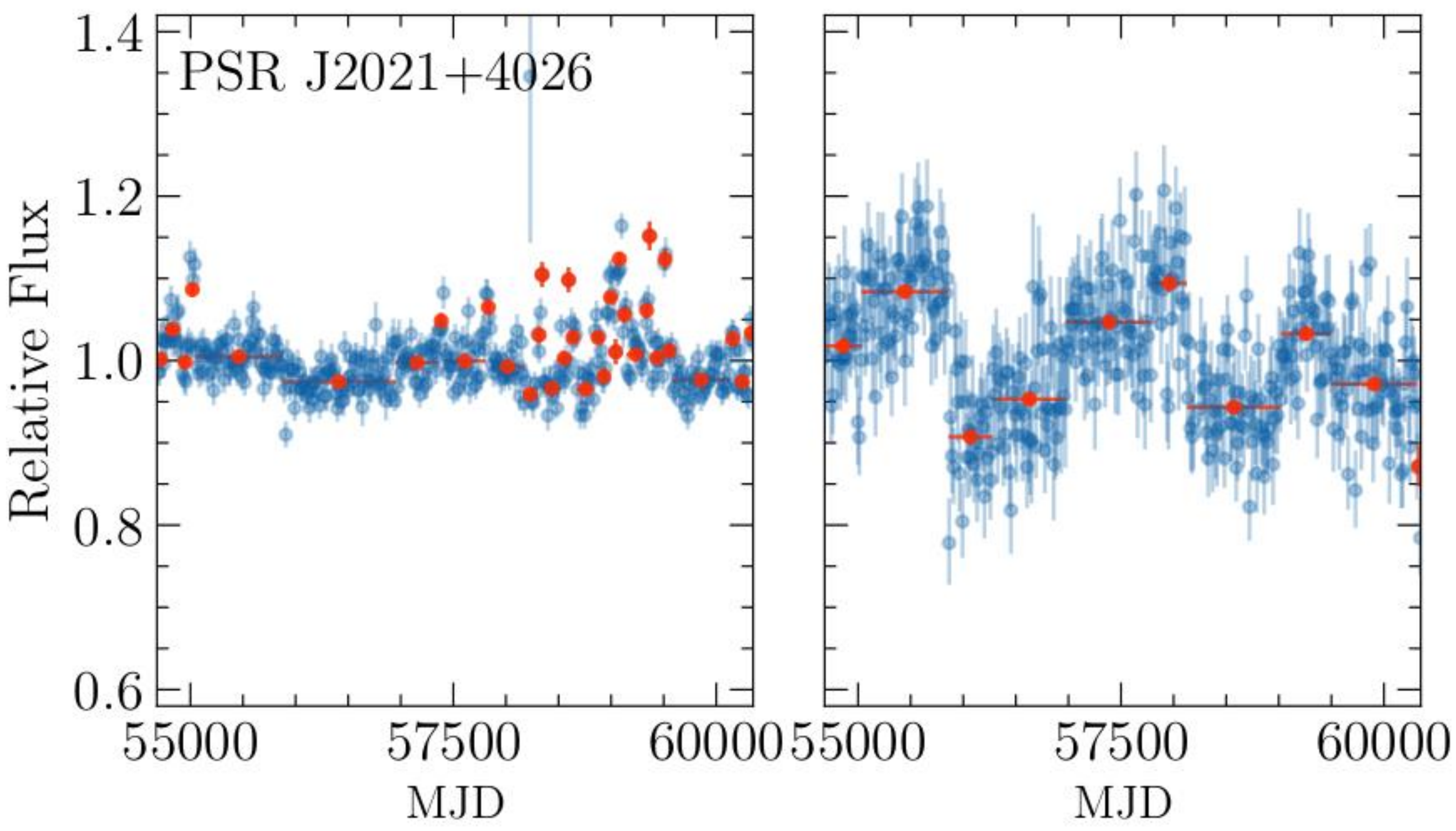
- The model is quasi-periodic with frequency $\frac{1}{f} = T_b + T_f$, and the "quality" factor of the process is determined by the width parameters: $Q^{-1} = (W_f + W_b)/(T_f + T_b)$.
  - The degree of asymmetry we call "t": $t \equiv T_f/T_b$.
  - The strength of the variability is governed by F_f/F_b. Null hypothesis is 1.

- For slow variability in this (or any model) we can just look directly for state (flux) changes.
- For fast variability, we can't see individual states.
  - Form power spectra density estimates (PSDs) and look for evidence of a stochastic process.

Two-pronged approach: (1) Slow Variability Search

Use the "weights" method of Kerr (2019).

- Allows rapid estimation of light curves and PSDs using photon weights (the probability that a photon comes from the source of interest).
- Apply Bayesian blocks to 2-week intervals to get adaptive light curve and update the weights.

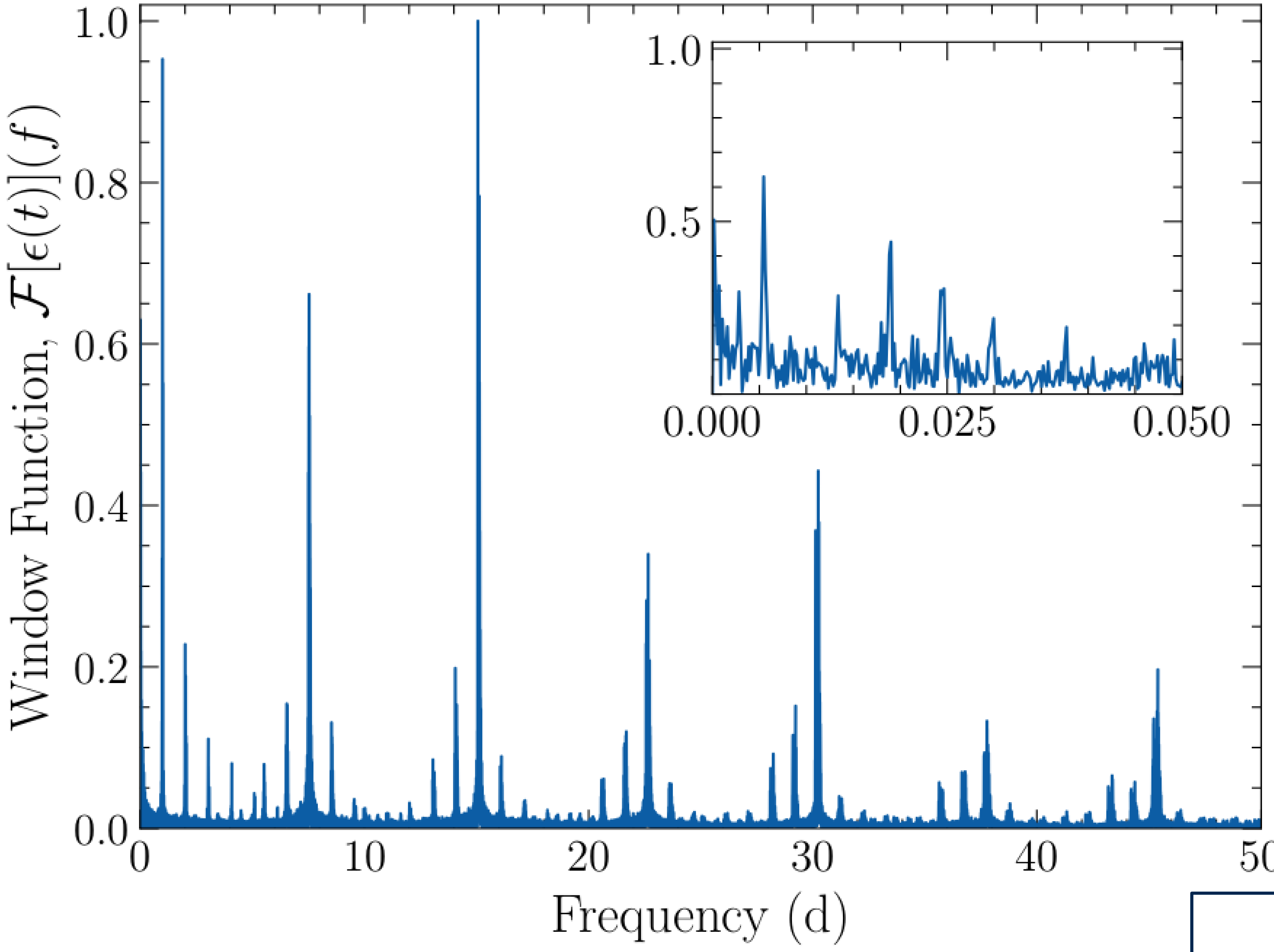


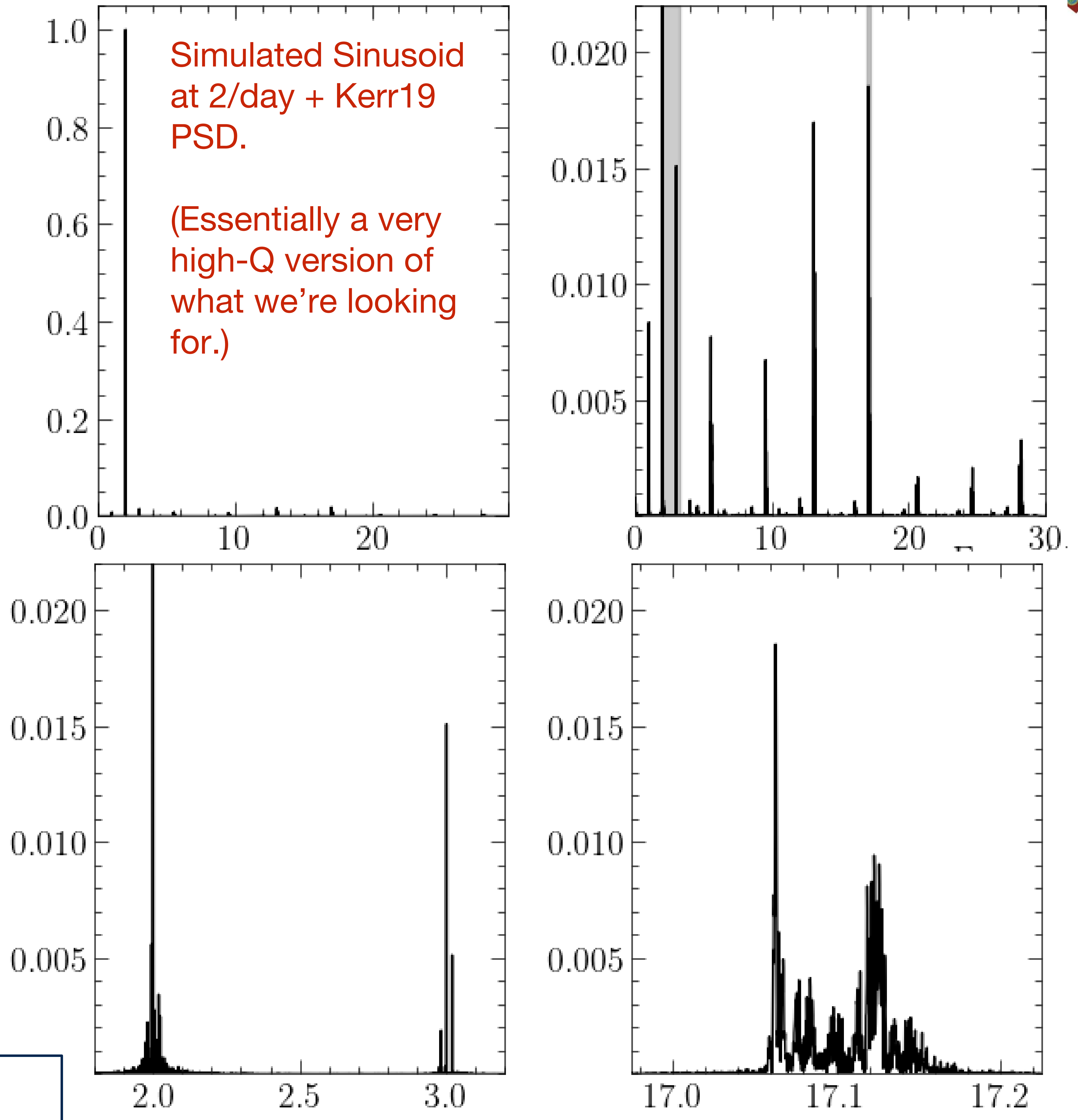
In this example, we first characterize background variations and re-weight the photons to filter them out.

Next, we characterize source variations: if the BB algorithm finds (reasonable) change points, we have evidence for variability!

Two-pronged approach: (2) Fast Variability Search or: PSDs with the LAT — Handle With Care

The LAT exposure pattern is essentially the window function: periodic signals, including low frequency noise, will leak to other frequencies.



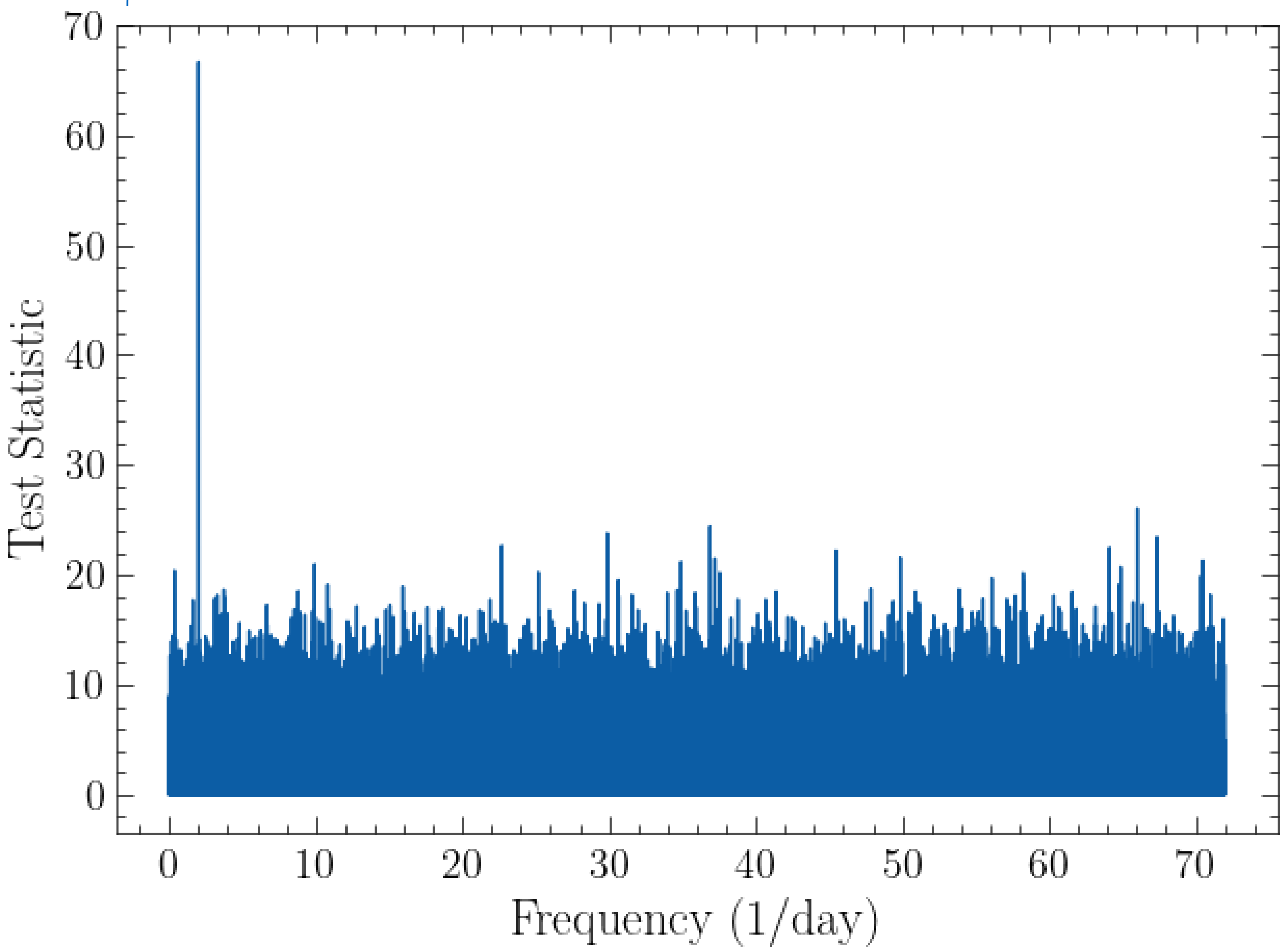


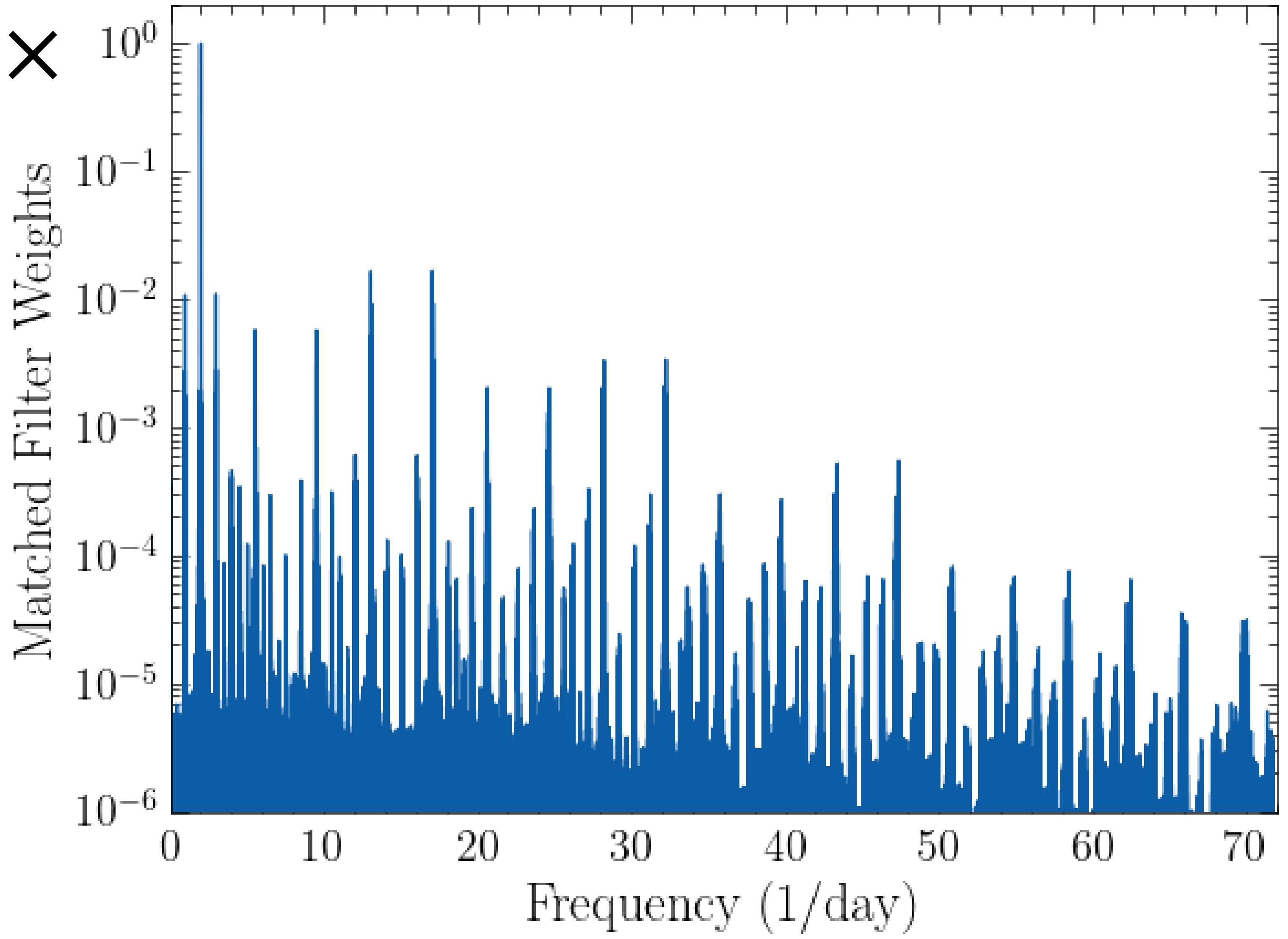
Lemons into lemonade:
turn window function into a matched filter

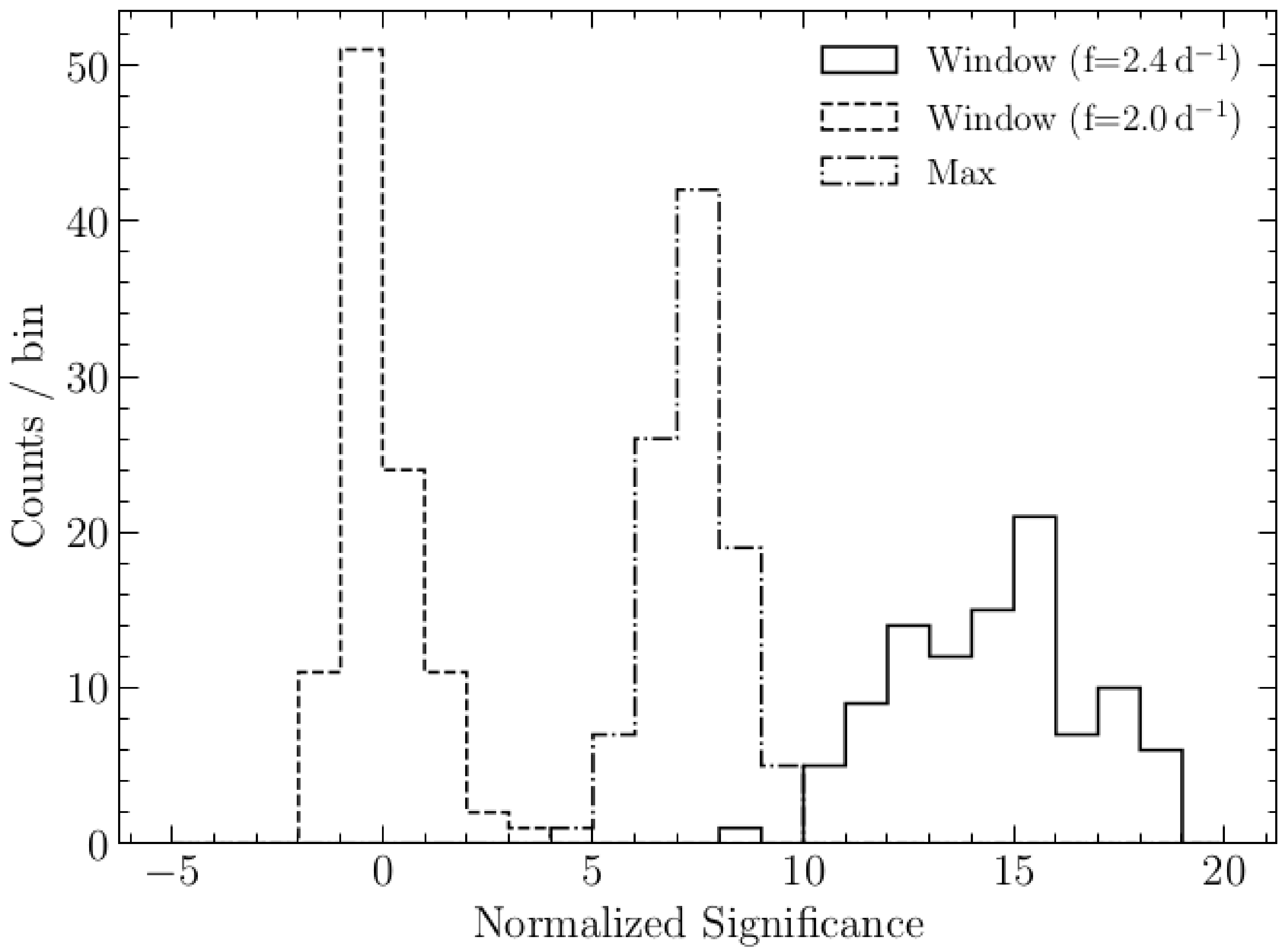
To detect this simple periodic variability, we could just search the PSD for peaks.

- But, all of that "leaked power" goes to waste.
- Instead, predict where the power should go and form a weighted sum/matched filter.
- Trivial with a periodic signal (window function) but <u>we can do it with more complicated models</u>.

SUM OVER ALL >360k FREQUENCIES





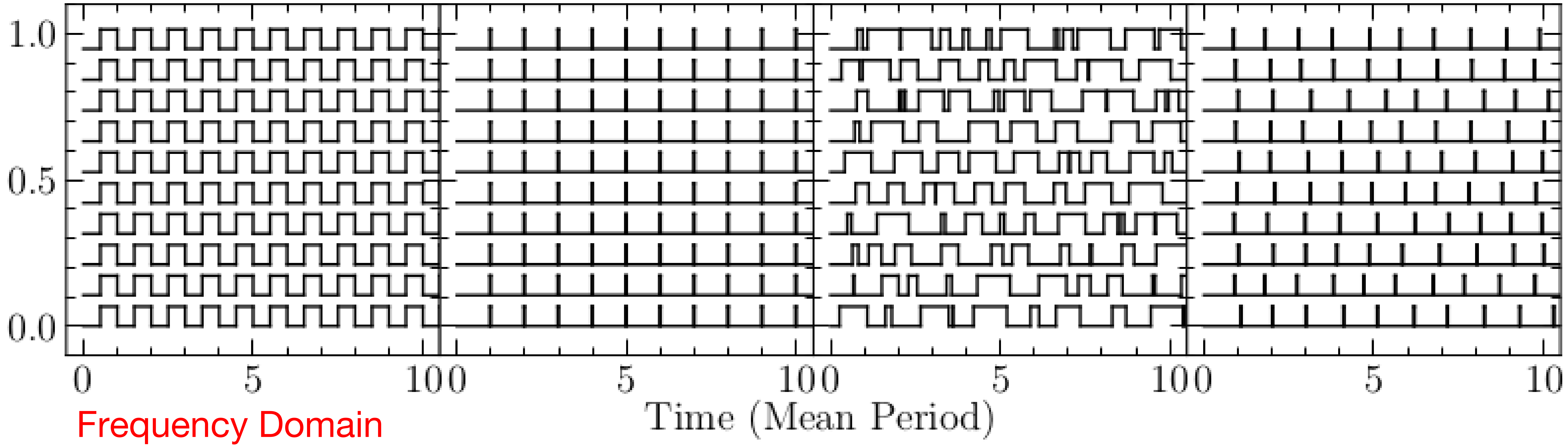


For this periodic signal, improves the significance (in sigma units) by roughly 2x!

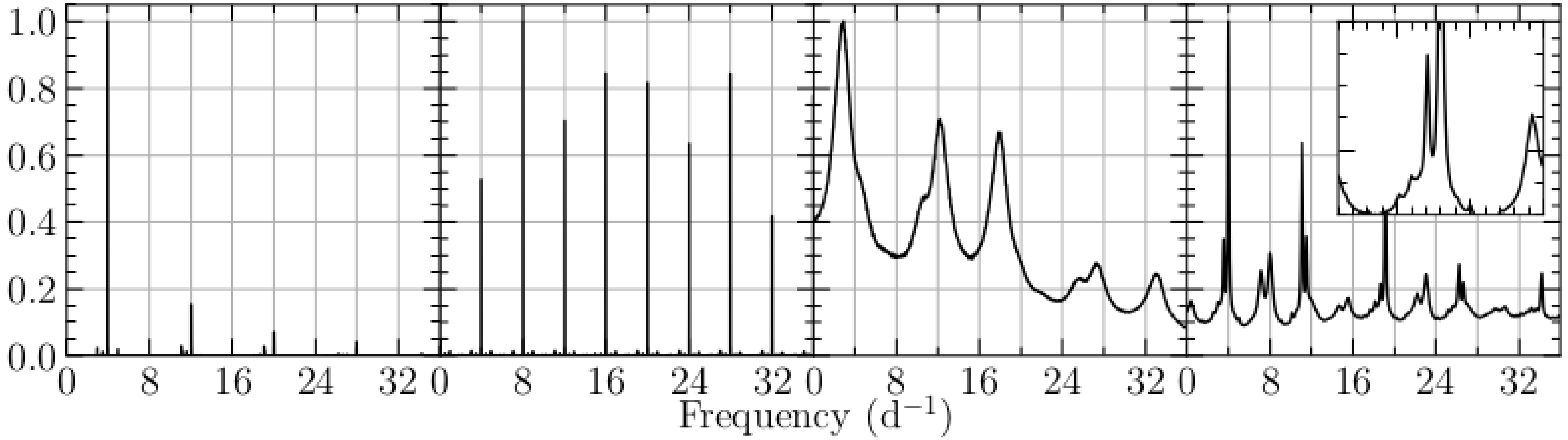
- This ought to decrease the threshold in flux by ~4x.

Example Matched Filters for 6-hour Variability

Time Domain



Frequency Domain



Each row shows about 10 cycles of an independent realization.

From Left:

- High-Q square wave
- High-Q asymmetric wave
- Low-Q square wave
- Low-Q asymmetric wave

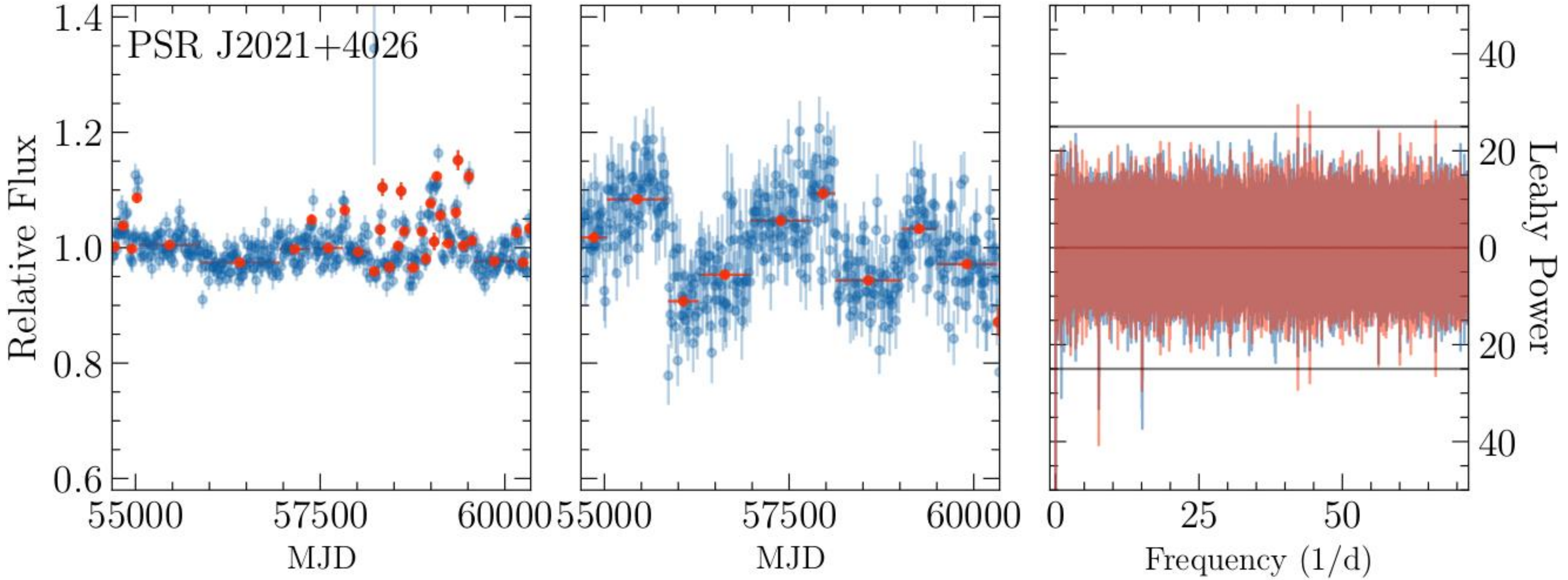
The mean PSD of many realizations of the random process.

If we had a "clean" measurement of the PSD, we could search for these processes efficiently.

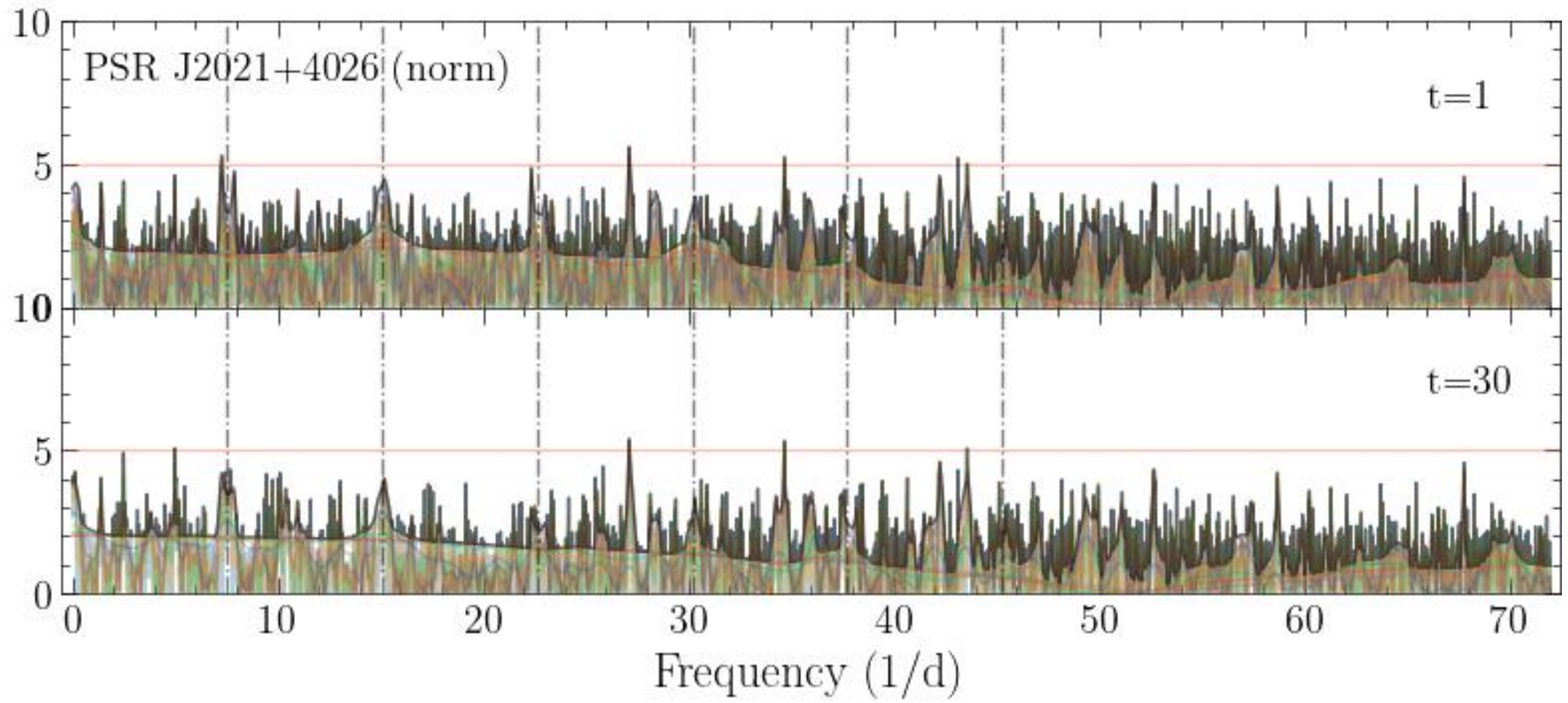
Final Piece: Slow Variability Output → Fast Variability Input

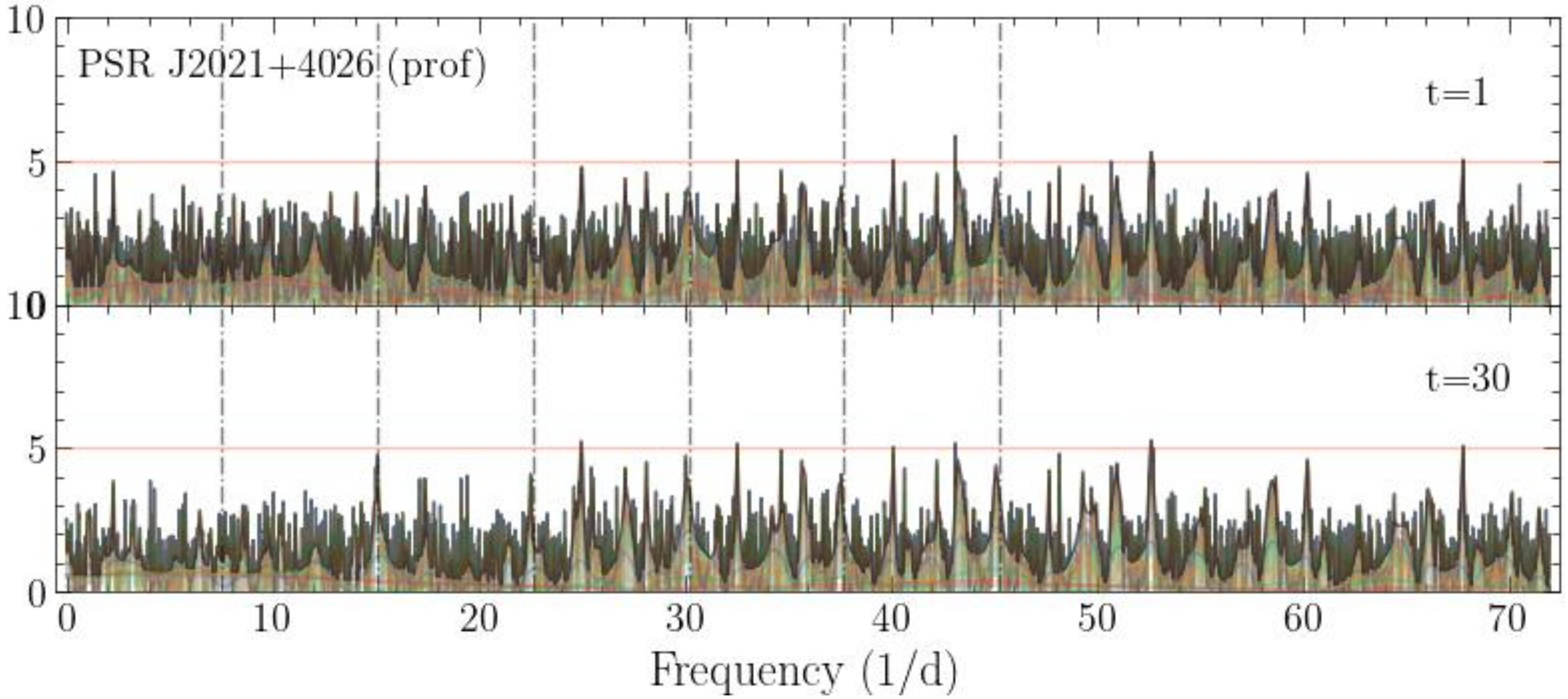
We don't want leaked power from slow signals showing up in our fast variability search.

- Use the results of the search to re-weight the photons and remove the slow variability in the time domain! The subsequent PSD won't suffer from spectral leakage.



Fast Variability Results

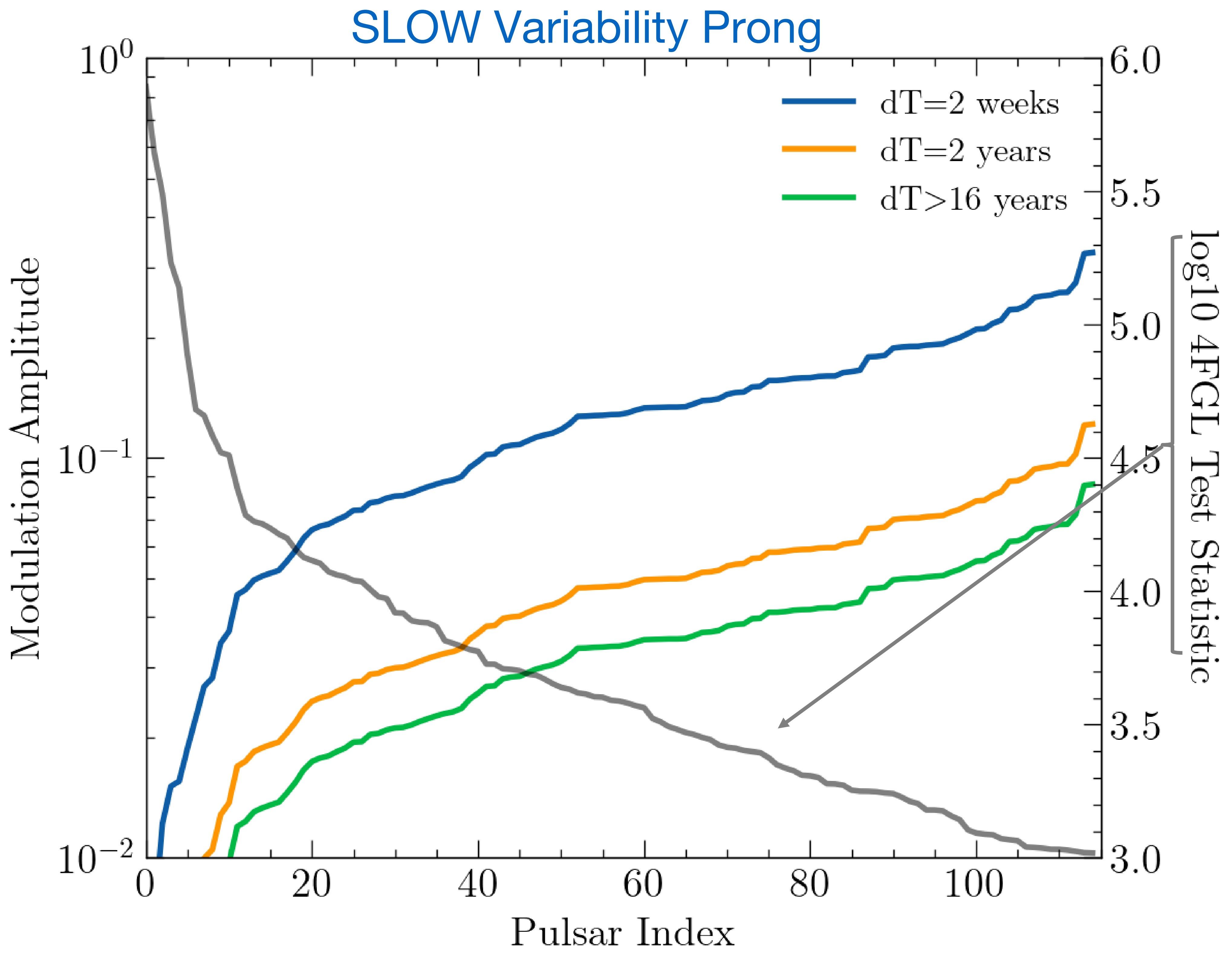


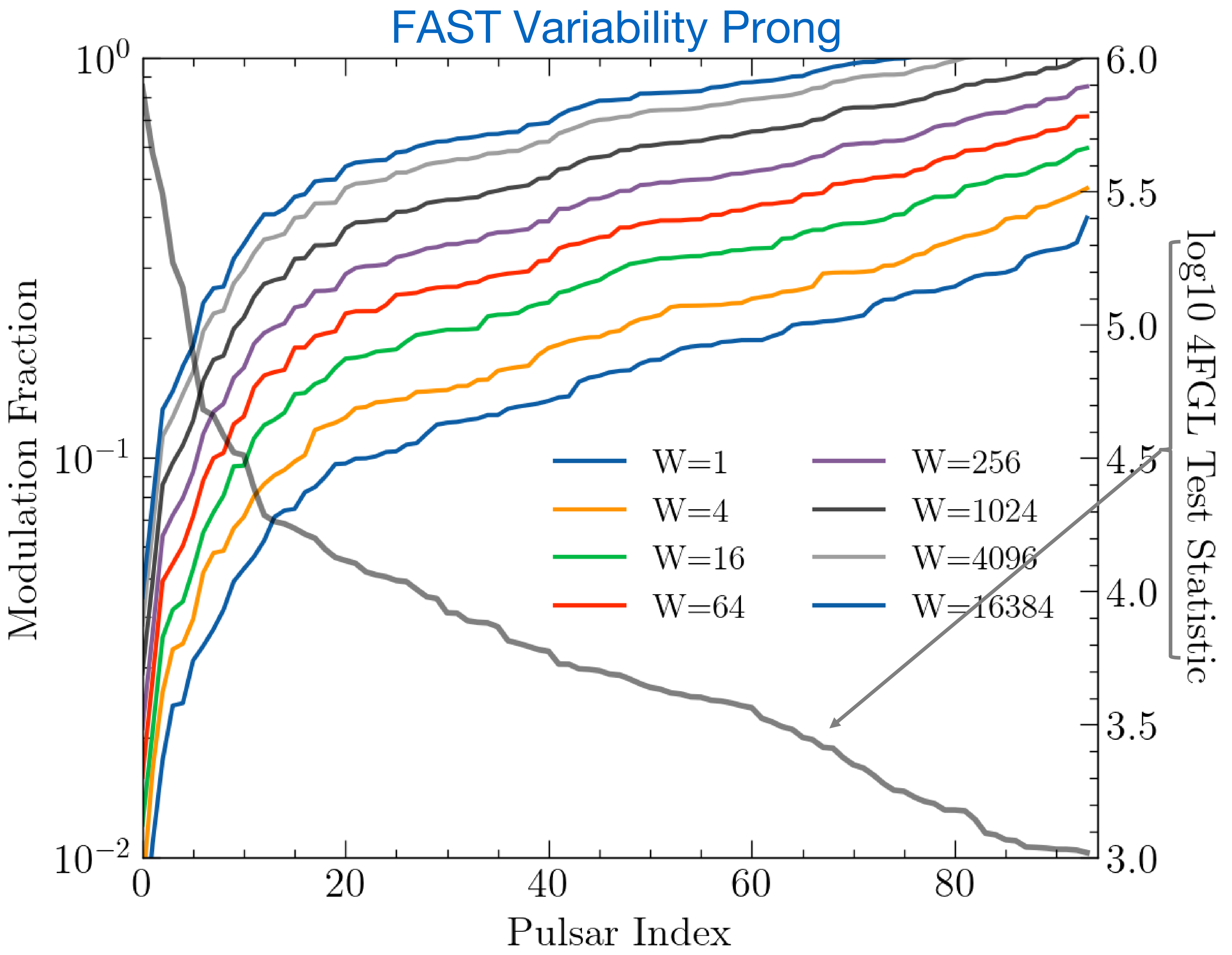


- These are the results of a fairly involved procedure!
  - Take the PSD from the pre-processing step, and then process them using a range of templates matched filters for different frequencies, asymmetry, and quality parameters.
  - Take the maximum at each frequency and convert to sigma units.
  - Top panel here is a square wave, bottom is a very asymmetric process. The periodicity is governed by the width of the template.
  - So here there is no signal at all!

Long/Short Term Results

- Generally, don't find any evidence for modulation. Thus, compute 95% limits on the typical flux modulation allowed at the various time scales.

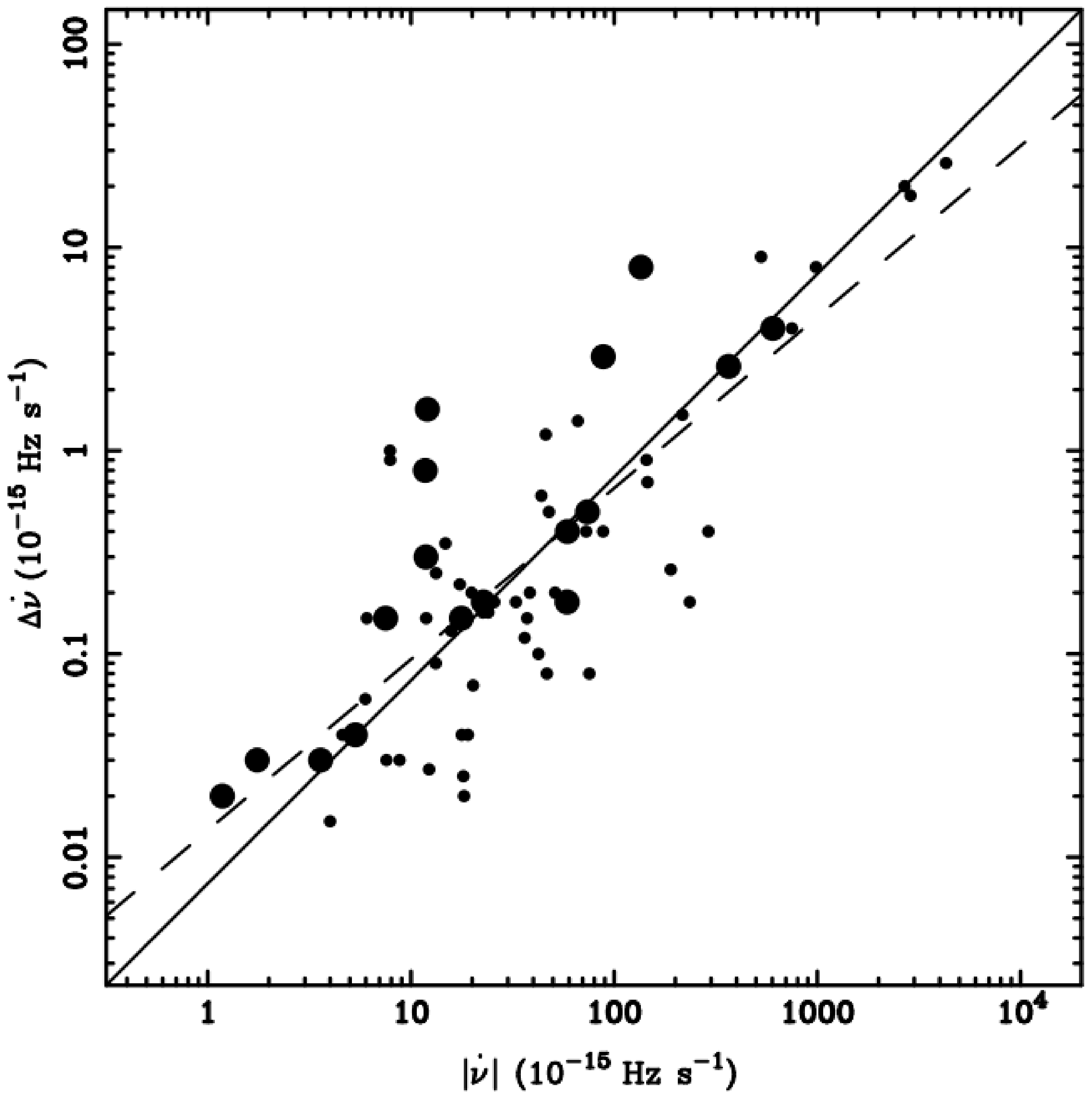




- Results ranked by pulsar brightness: rule out few % fluctuations on slow time scales. On fast timescales, rule out few % fluctuations only for brightest, or most coherent processes.

Conclusions and Future Work

- We essentially rule out model-independent variability on time-scales > 2 weeks.
  - Constraints at the few-percent level for a sample with N>100.
    - No intermittent pulsars; Lyne+ 2010 variations (1% with large scatter) constrained to low end of amplitudes, or faster timescales.
  - J2021+4026 is a unique!



- No evidence for quasi-periodic variability on timescales down to minutes.
  - Due to trials factors, limits range from few percent to few tens of percent.
    - Lyne+ 2010-like variations modestly constrained for brightest pulsars.
    - Nulling ruled out at all timescales (down to minutes).
      - Kerr (2022) provides similar results on single-pulse time scales.

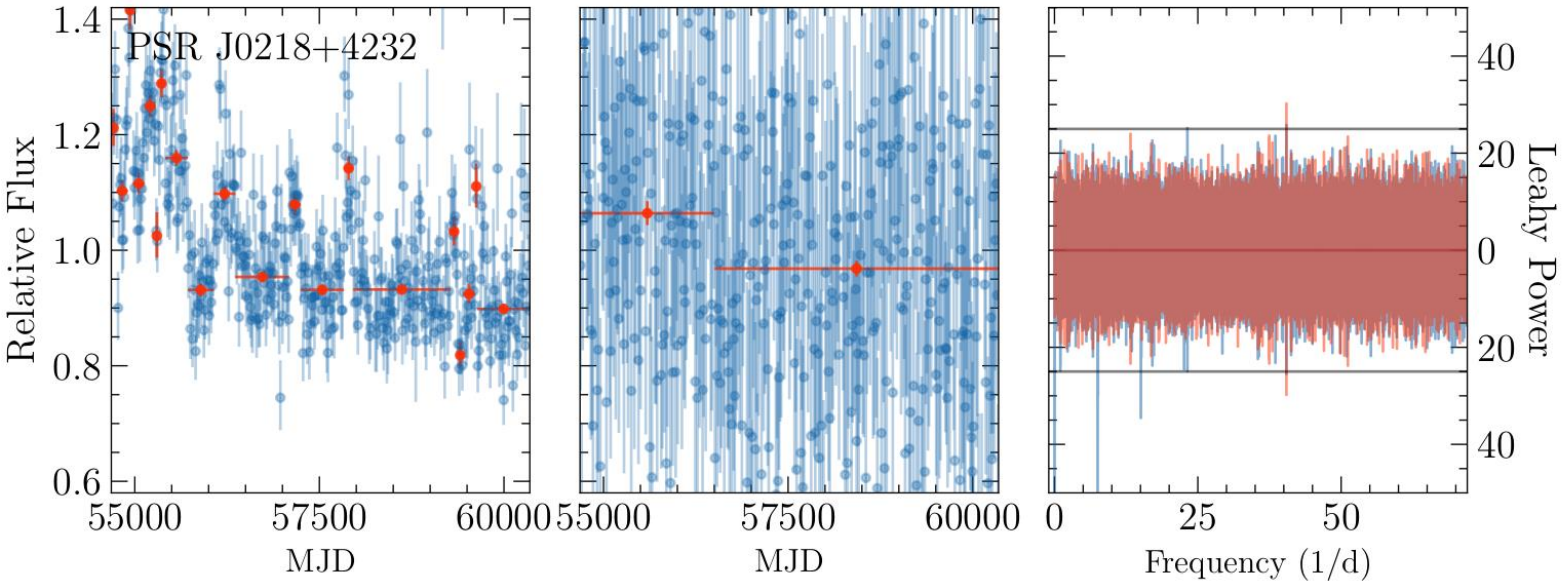
- Open questions:
  - Why is J2021+4026 special? If timescales are tied to e.g. magnetic field evolution, should see similar variability in other pulsars.
  - Can <1% level variations be detected? Potentially yes, if also using pulse phase information and/or correlated pulsar timing. Future work!

Backup Slides

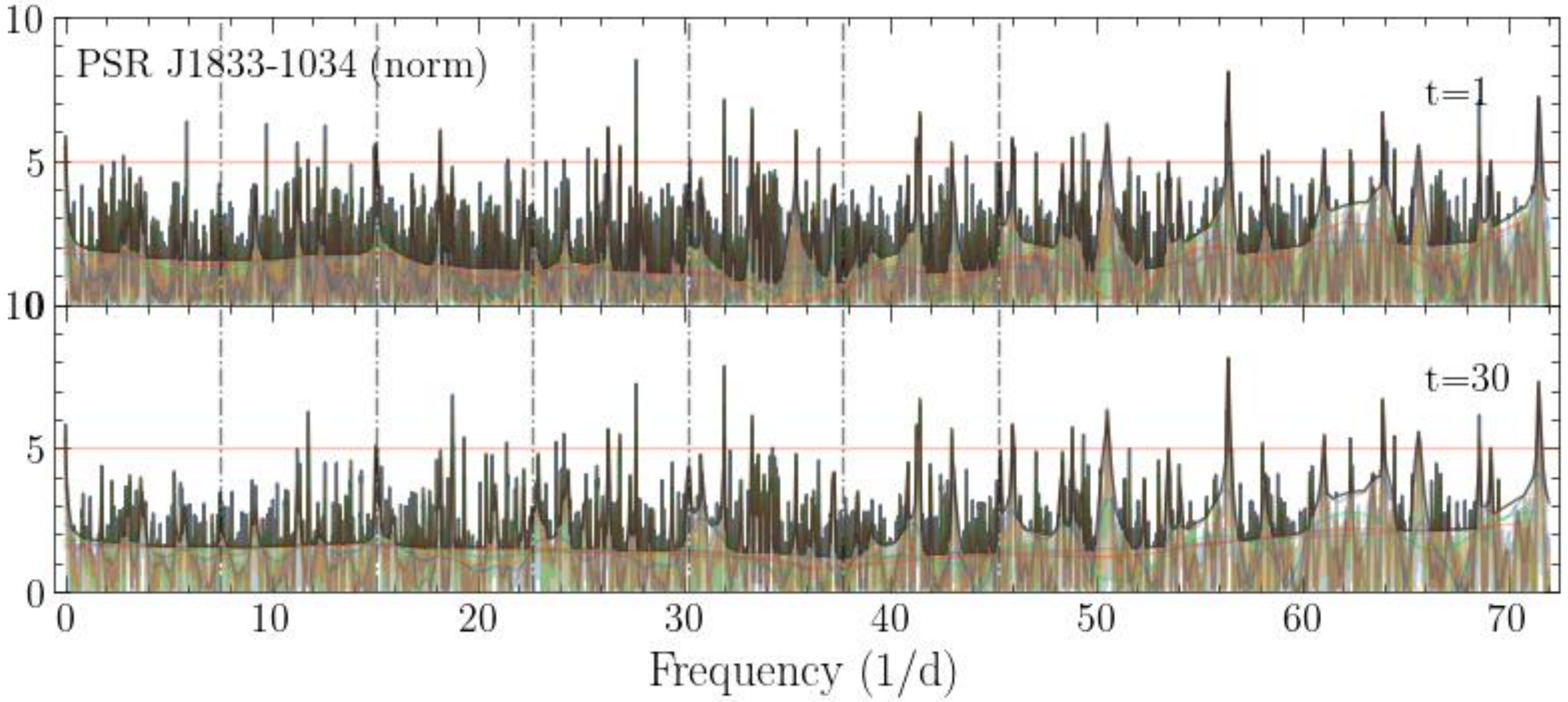
Final Piece: Slow Variability Output → Fast Variability Input

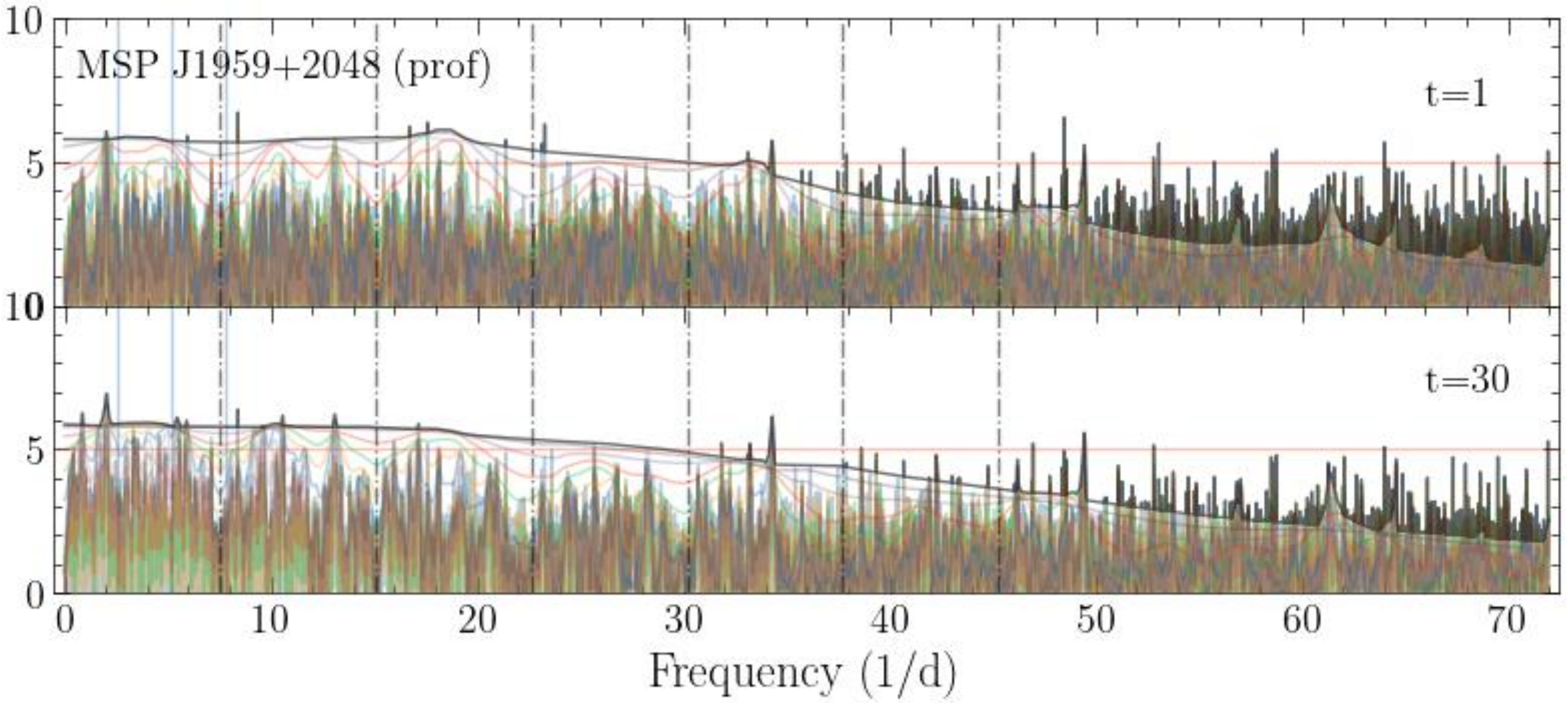
We don't want leaked power from slow signals showing up in our fast variability search.

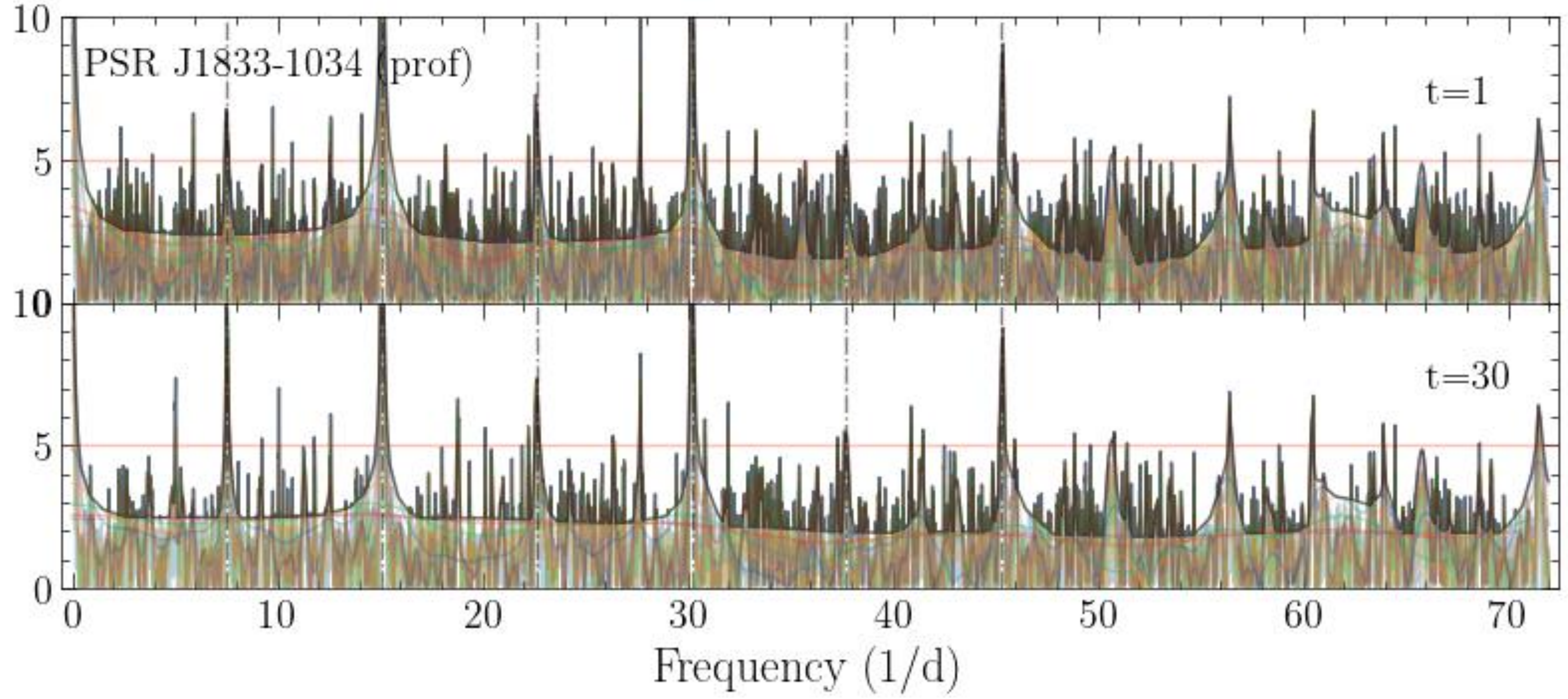
- Use the results of the search to re-weight the photons and remove the slow variability in the time domain! The subsequent PSD won't suffer from spectral leakage.

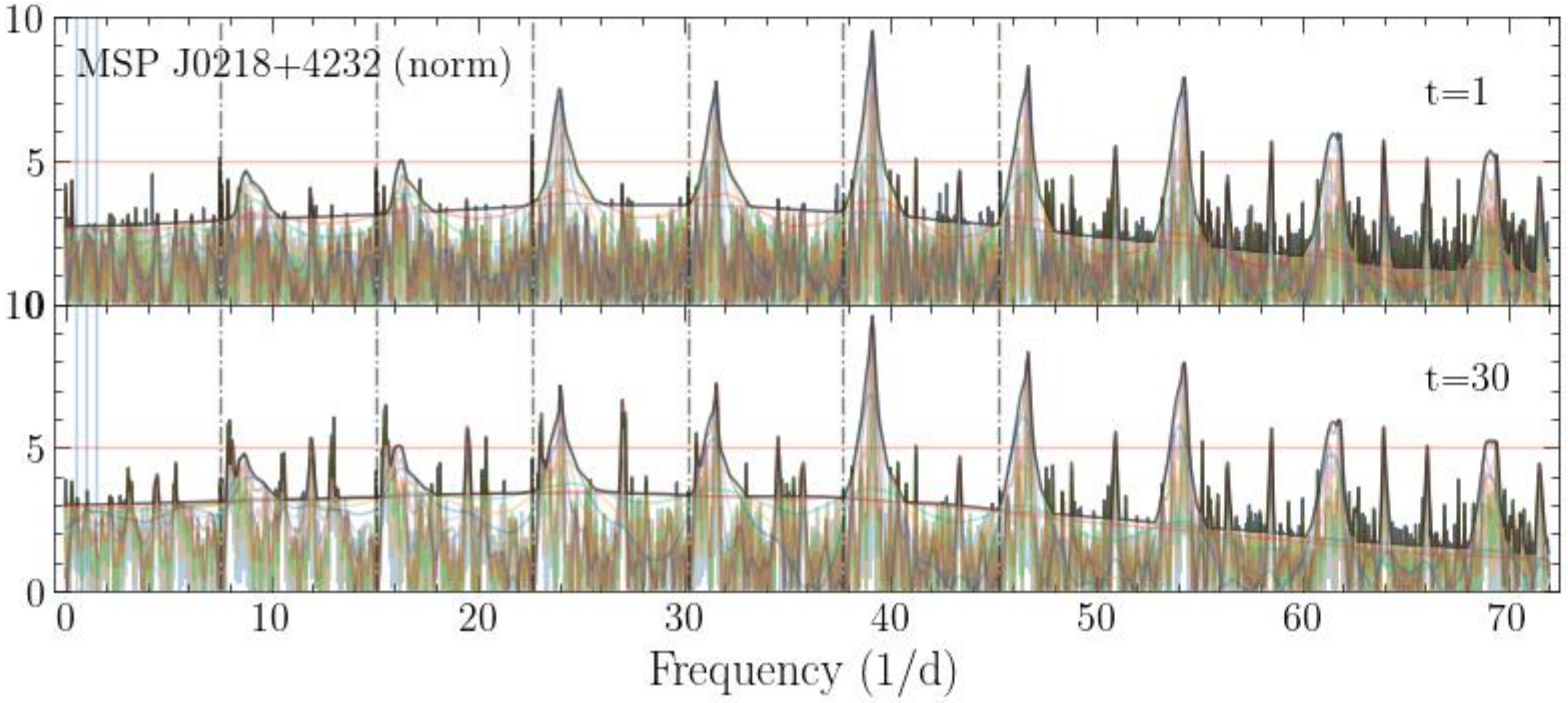


Some more examples…



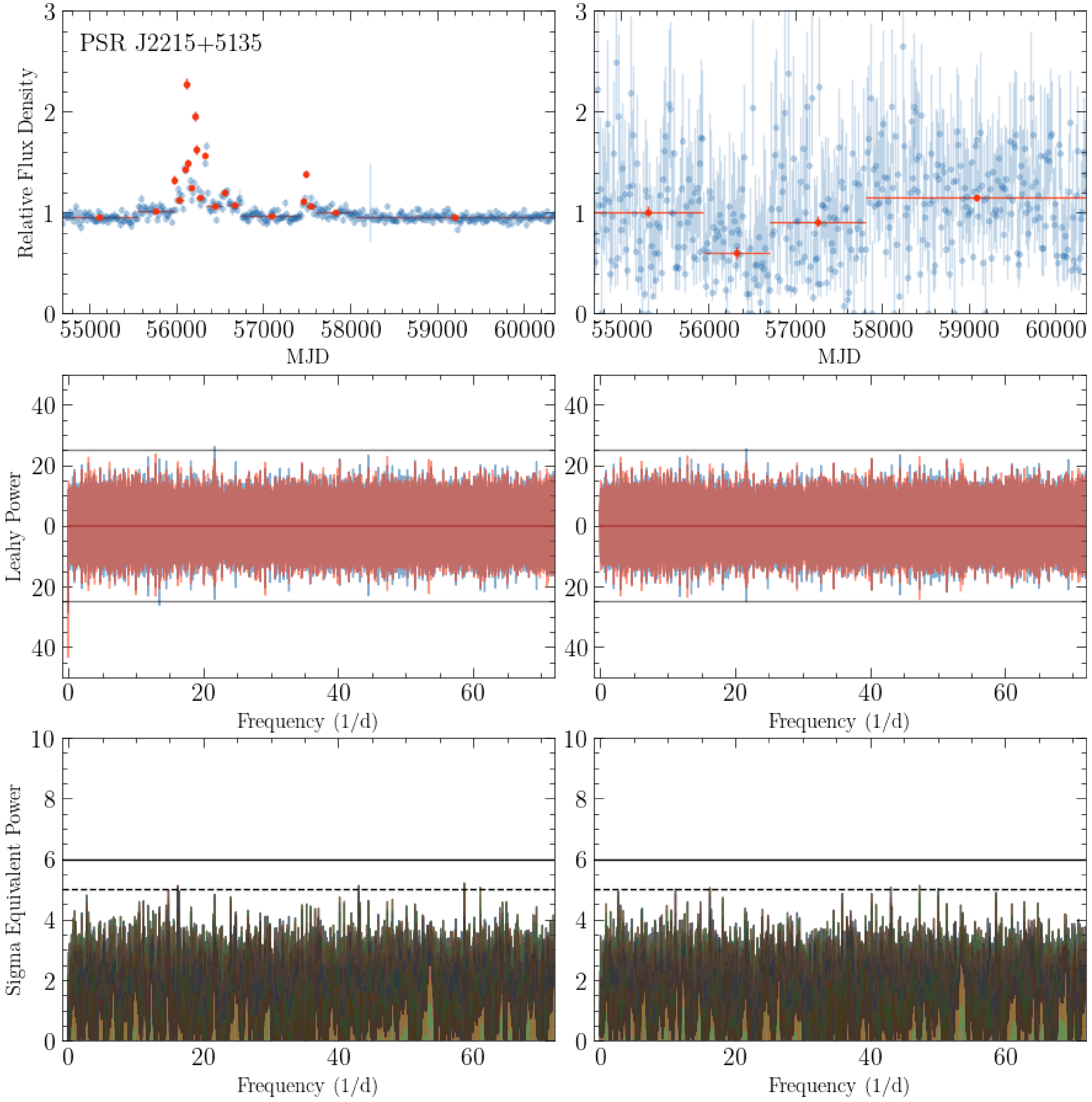






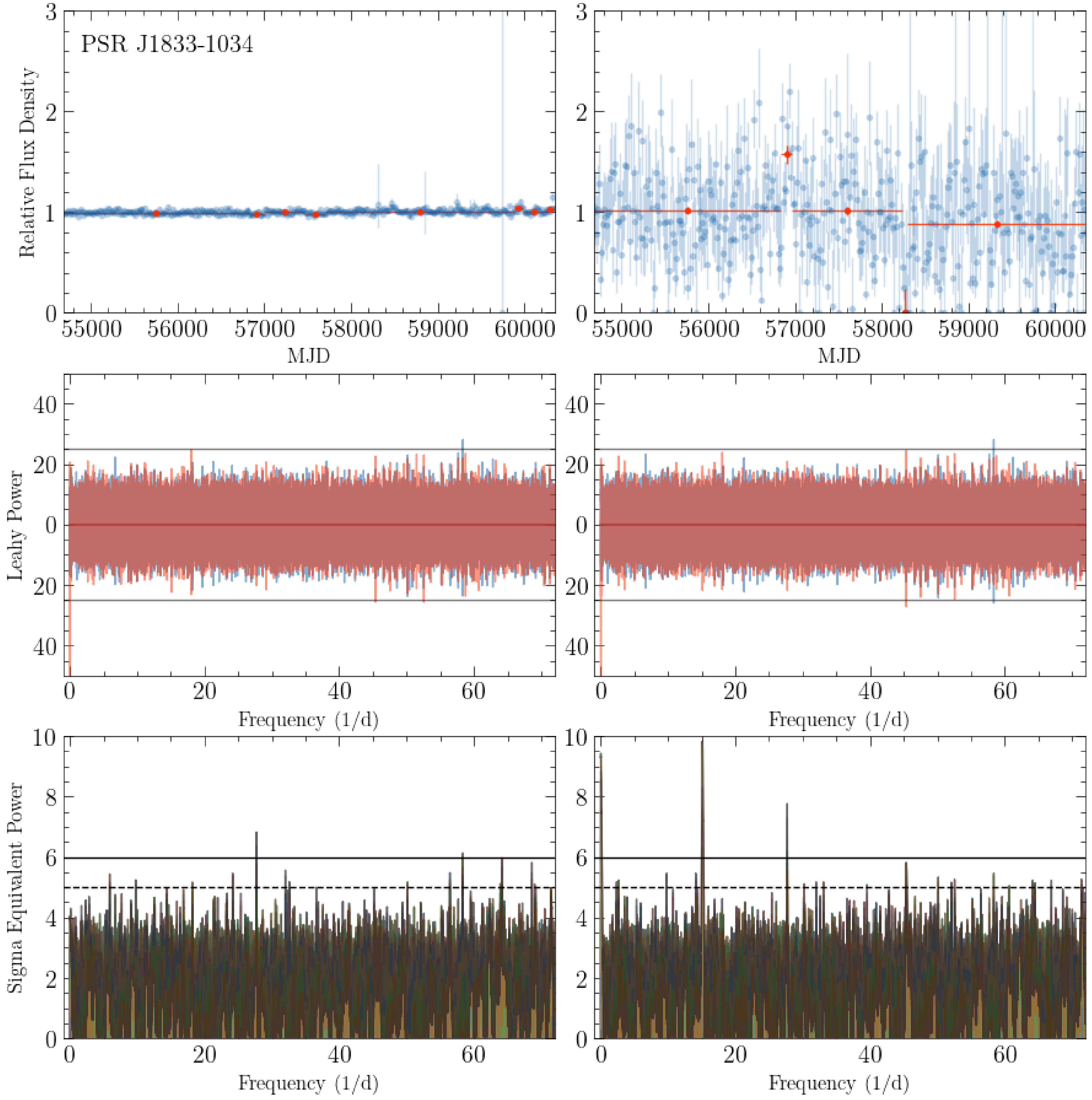
A few problem cases…

Imperfect separation of source/background: strong background flare leaves imprint. Contaminates long-term variability analysis, but power still seems clean.



More source/background confusion. Potential issues in source light curve, but bigger problem is the background-profiled likelihood: it's higher than the "raw" likelihood!

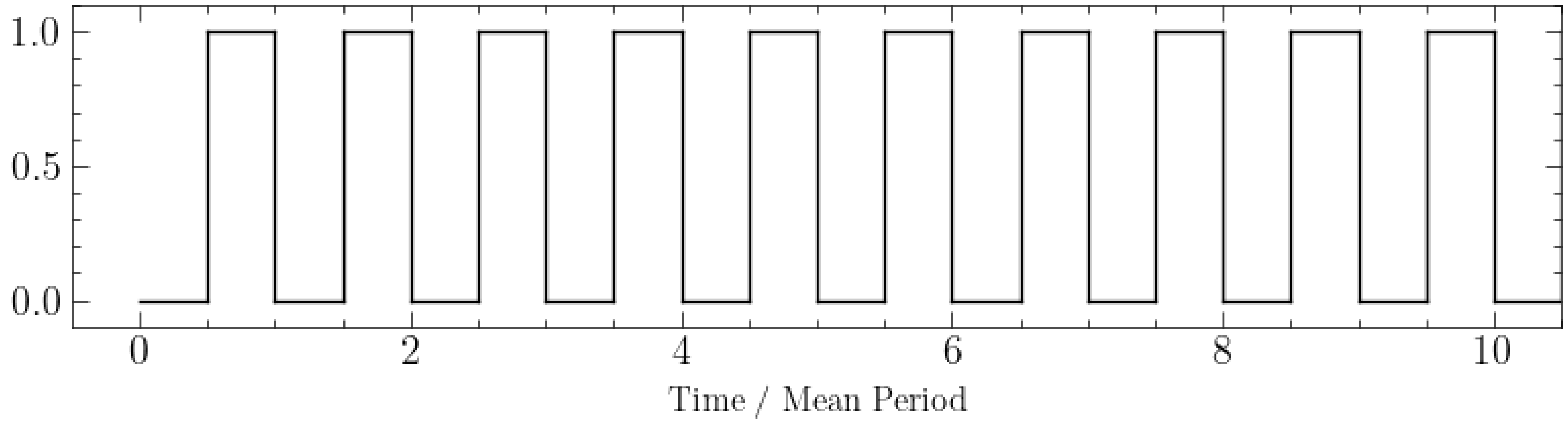
Solution: do downstream searches with both versions and compare the results.



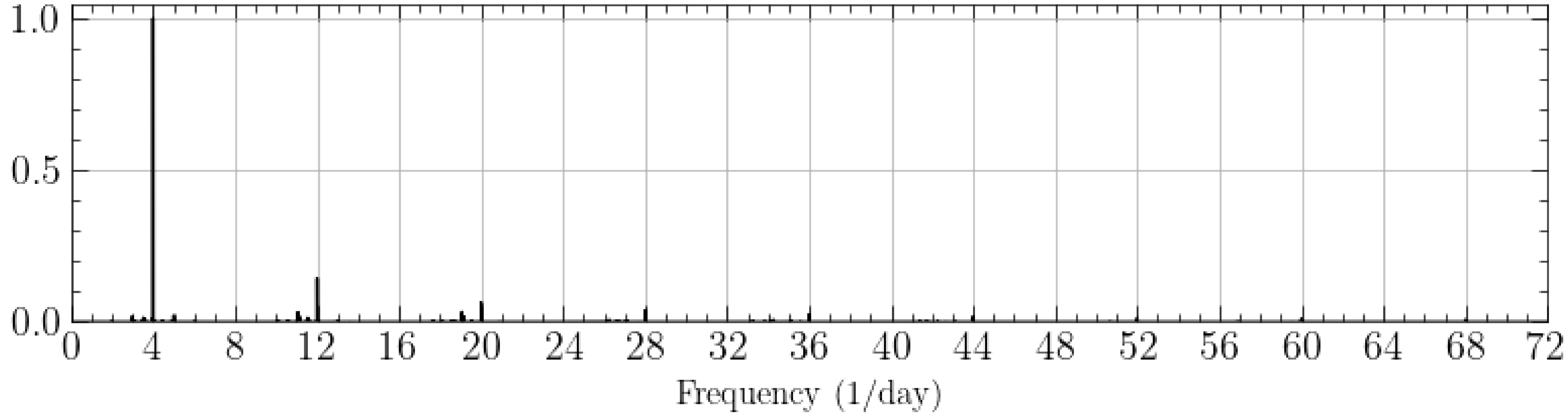
Examples

- Let $T_f = T_b = 86400/8$ → fundamental frequency f = 4/day
- If $W_f = W_b = 0$, ($Q \to \infty$) it is a perfect square wave.
- Analytically: square wave has power only even harmonics.

Time Domain (zoom)



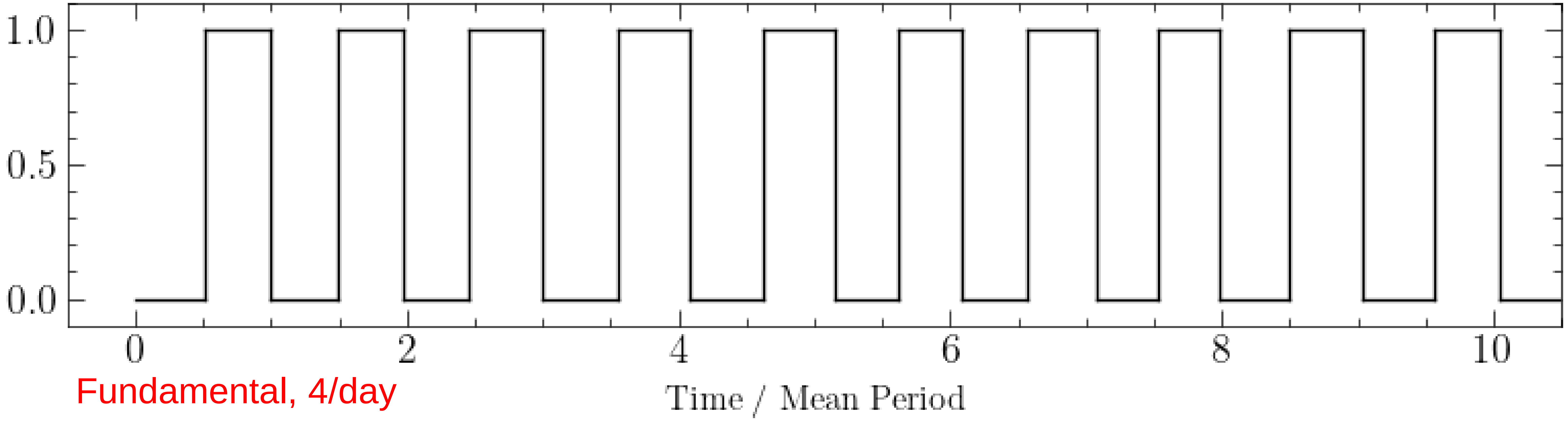
Matched Filter



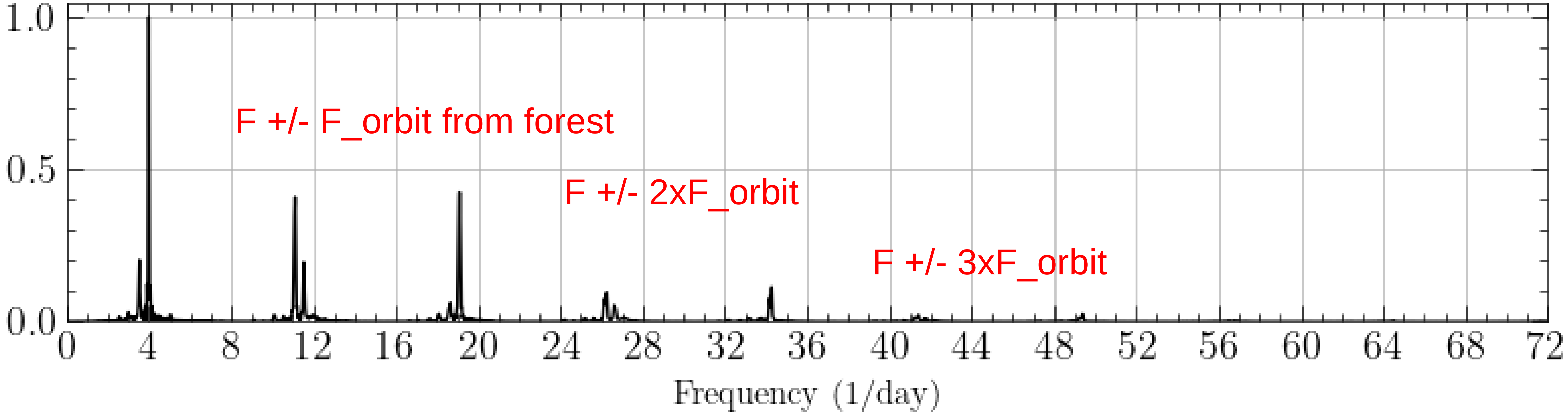
Examples

- $T_f = T_b$, f = 4/day, but now add a random element: $\frac{W_f}{T_f} = \frac{W_b}{T_b} = \frac{1}{10}$, or $Q = 10$.
- Essentially a convolution of the $Q \to \infty$ shape with a broadening function.
- This causes MUCH more power to show up at the leakage frequencies, because it averages all that forest of power together.

Time Domain (zoom)

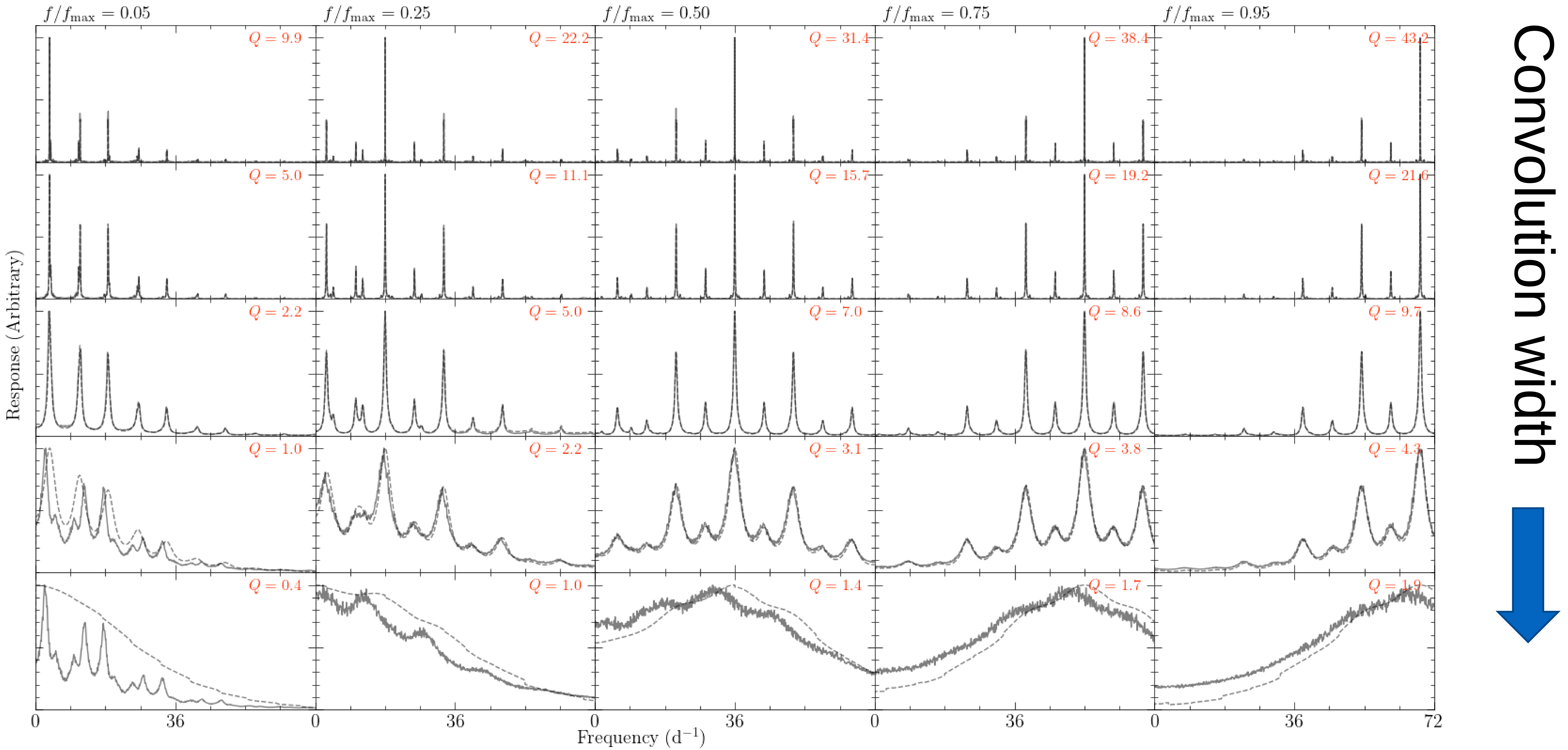


Matched Filter



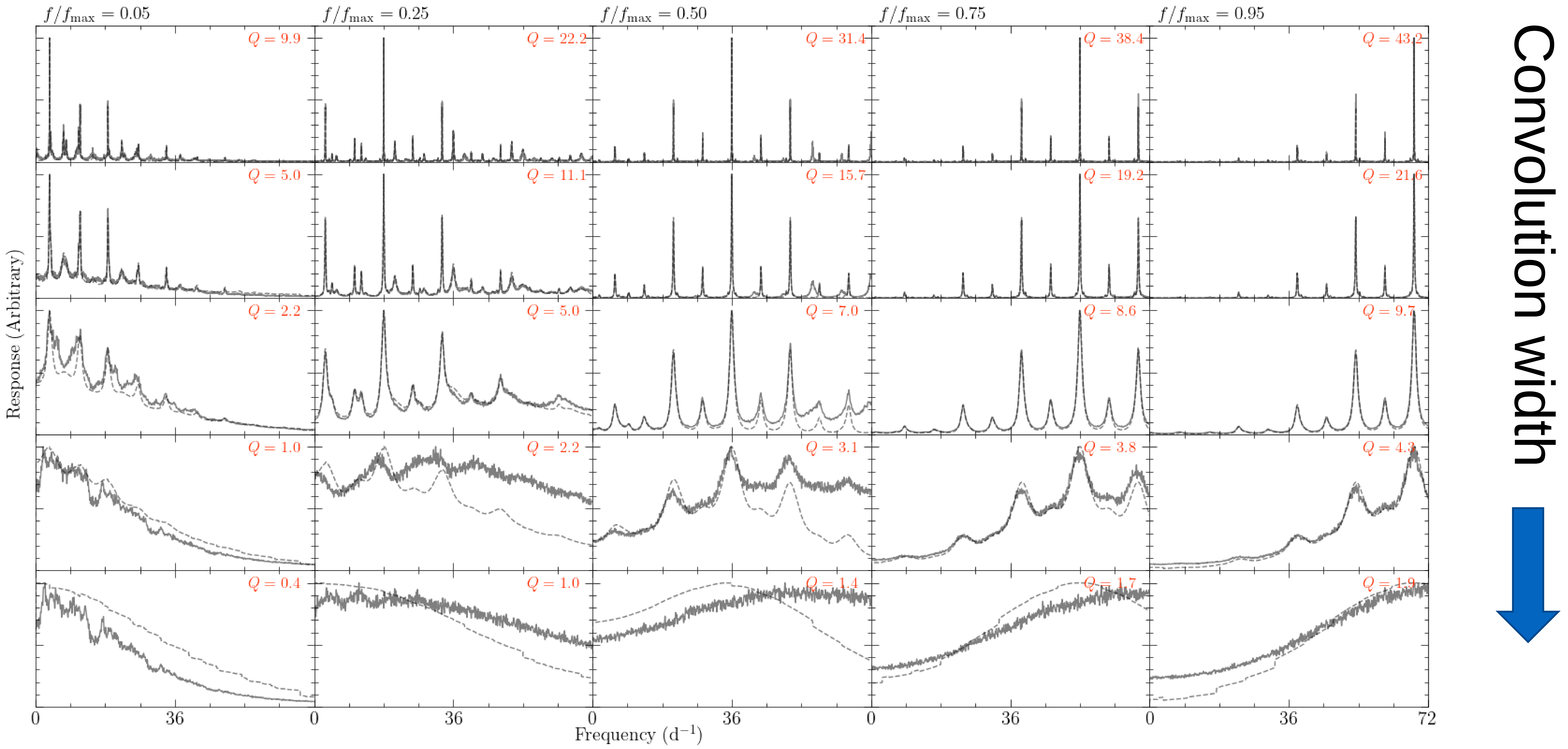
Comparing Model w/ Simulation

- $T_f = T_b$: a scan in convolution width and frequency covers all f & Q values



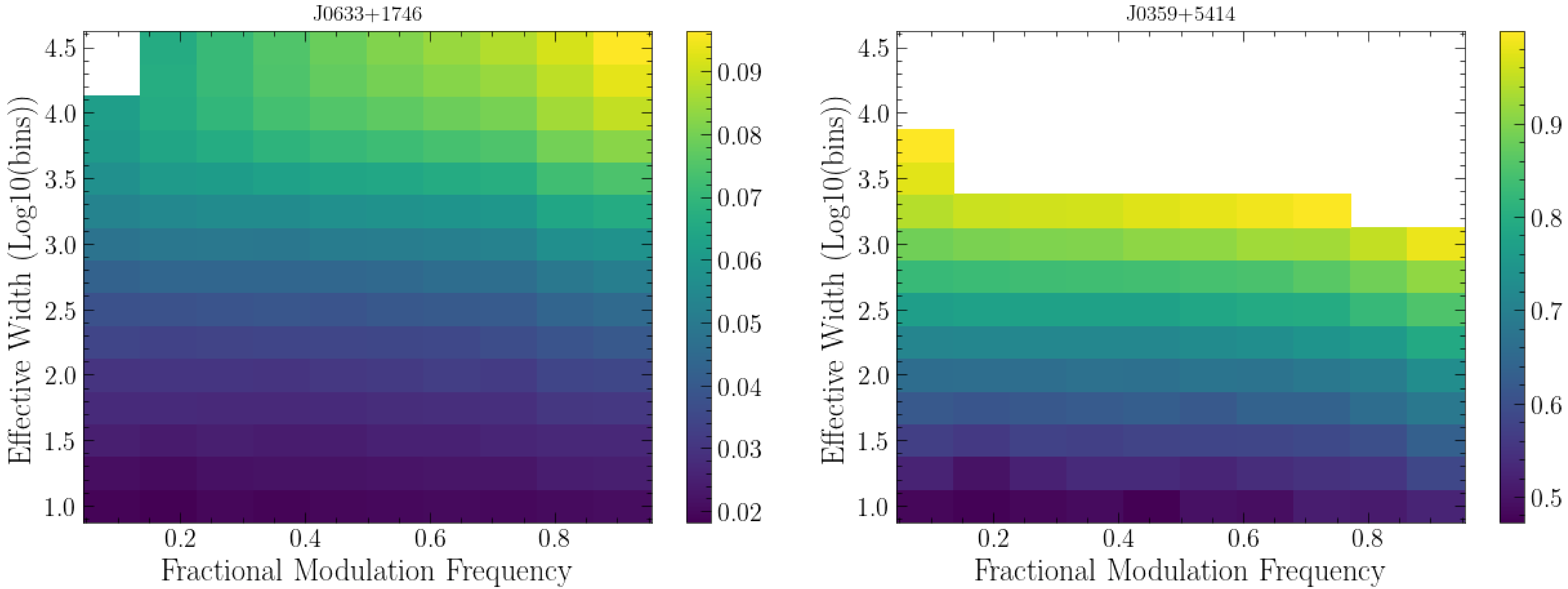
Comparing Model w/ Simulation

- $T_f = T_b \times 10$ (t=10), width varied from bottom to top: 100 bins, 400, 2000, 10000, 50000



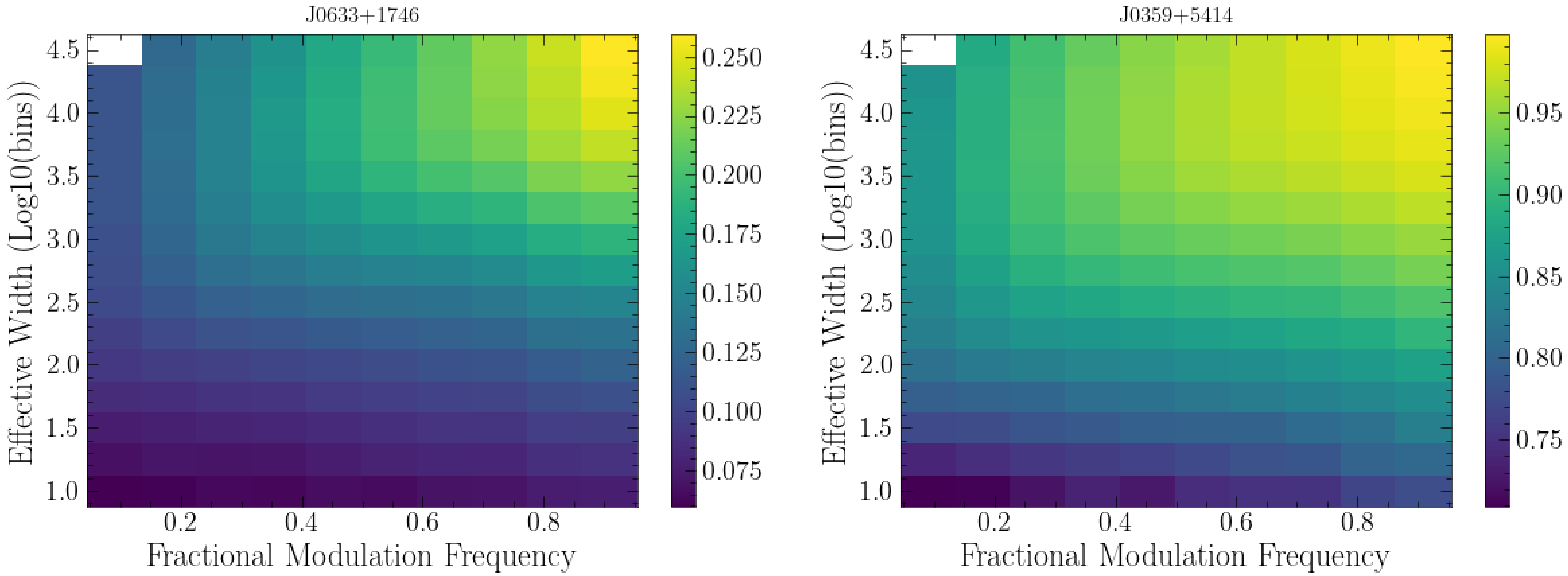
Upper Limits (5-sigma Threshold)

- t = 1:mild dependence on frequency, strongest dependence on W.
  - Geminga: can detect few-percent modulations over whole parameter space.
  - J0359+6414: a TS~1000 pulsar; require at least 50% modulations, and “low Q” processes not detectable (require >100% modulation).



Upper Limits (5-sigma Threshold)

- t =10: roughly 3x reduced sensitivity.

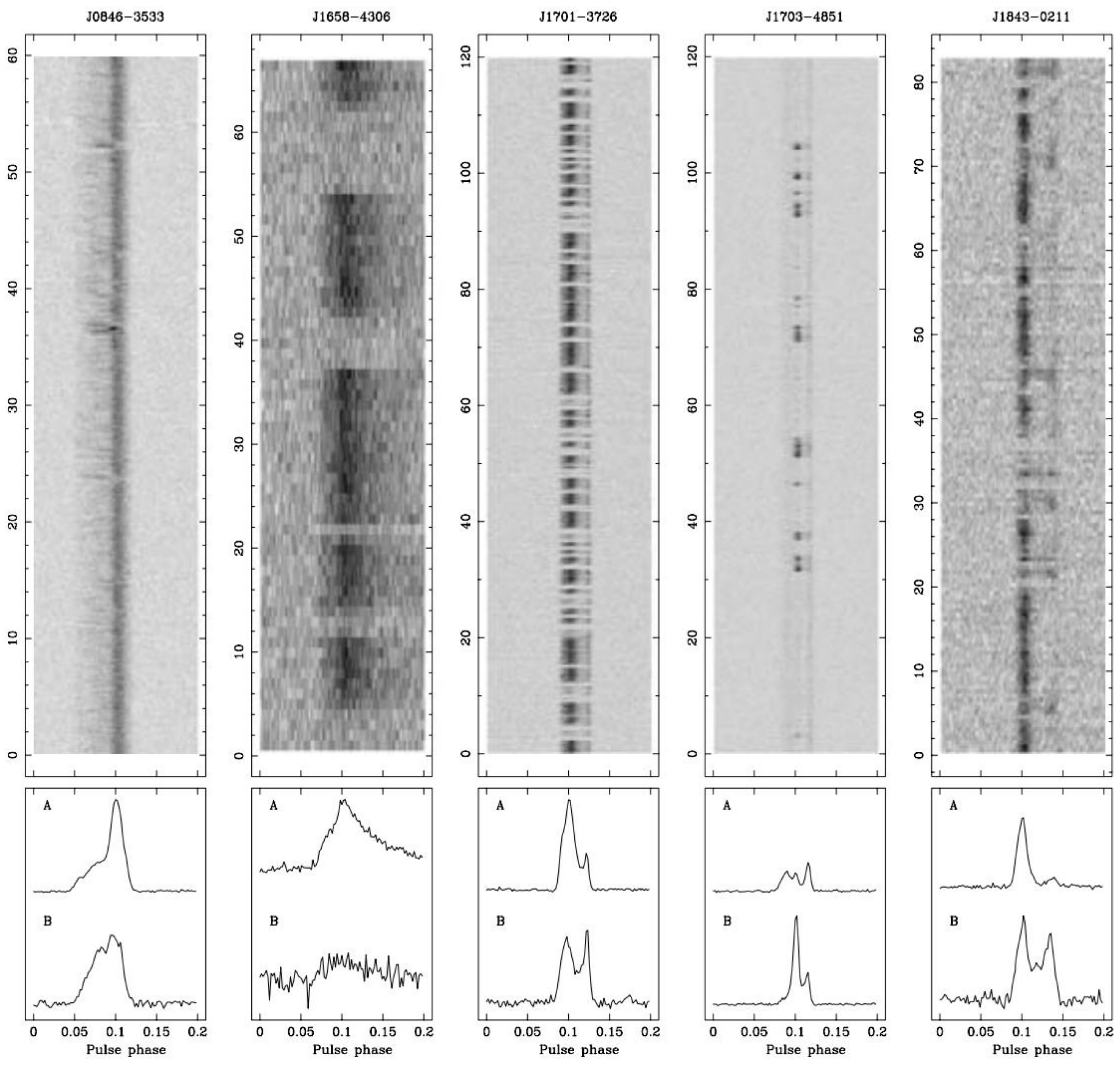


Sensitivity Calculation

- Can simulate the exact realization in the data for any of the model parameters.
  - A "noiseless" spectrum obtains from by simply using the predicted source counts rather than drawing a random variable.
  - Still has random element because the switching times are still random. Thus, do enough iterations to "average over" the process.
    - This gives both the "matched filter" AND the expected signal strength.
- If a = F_f/F_b, then the variance of the time domain signal is Ptot = (1-a^2)/(1+a)^2. This relates the model parameters to the total signal strength.
- The other piece is: given the matched filter with normalized weights w_i, the effective degrees of freedom are dof = $\frac{2}{\sum_i w_i^2}$.
- The upshot is: one can calculate the chi^2 for a=0 (full strength) and a=1 (chi^2=dof) and then simply solve for the 5 sigma value to obtain the 5-sigma threshold of "a".
  - Can do this for different frequencies, time ratios, widths…
    - An efficient way to determine the sensitivity for any given pulsar.

Radio Pulsars: Mode Changing a Relatively Widespread Phenomenon

- An observational definition of radio pulsar mode changing:
  - Switches between two or more (but two is typical) states characterized by different flux density, profile shape, and polarization.
  - Timescales range from ~1 pulse to years.
    - Typical values are minutes to hours, tied to observational considerations.
- Is this just a coherent emission curiosity, or does it mean something for the pulsar engine?



Wang, Manchester, Johnston (2007)