Searching for bursts: algorithms, vetoes, upper limits

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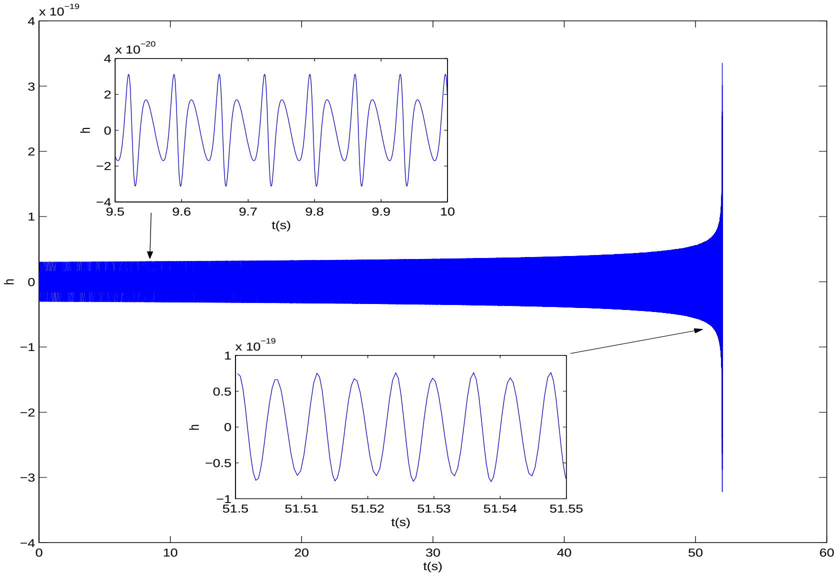
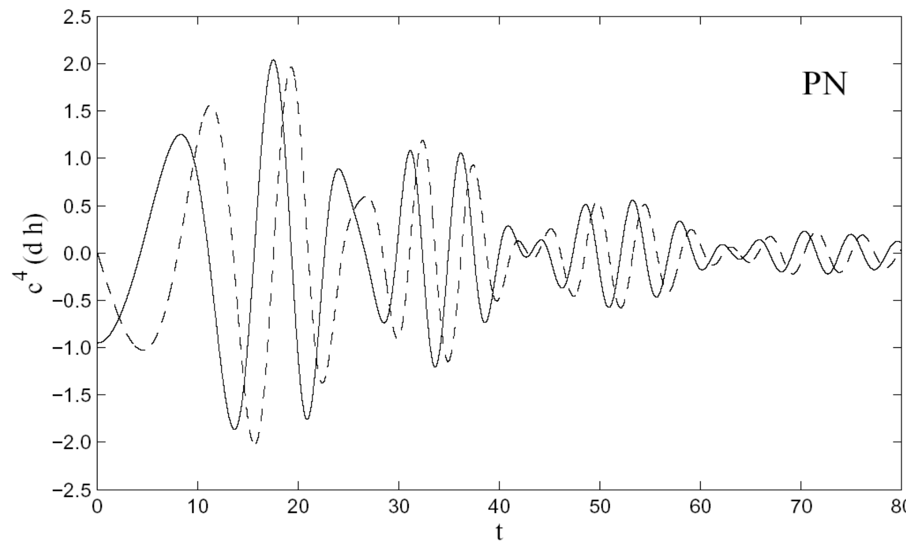
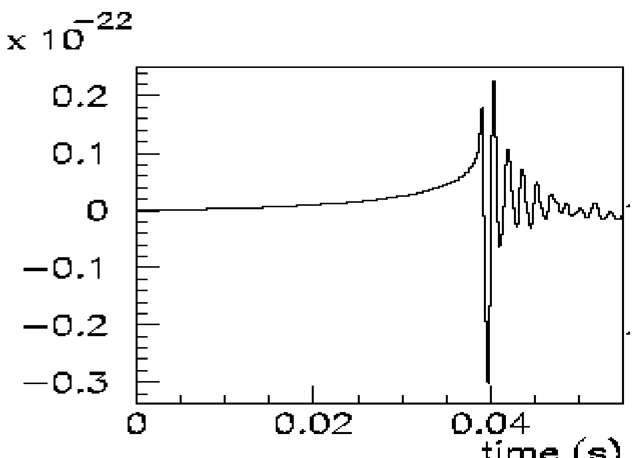
Bursts

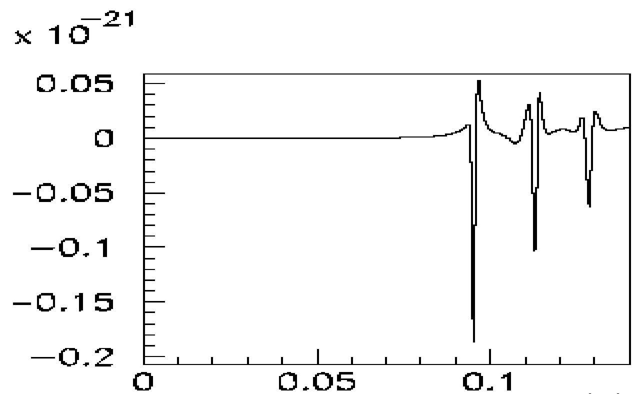
- short GW signal (milliseconds to tens of seconds), with some frequency component in the 10-1000 Hz band



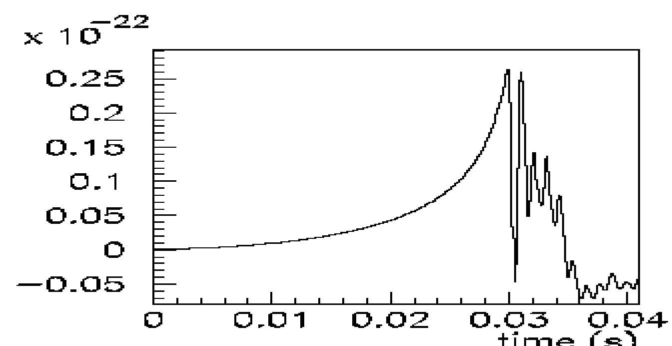




TYPE I



TYPE II



TYPE III

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Signal detection: definitions

- Choose between two hypotheses:

$$H0: y = n$$

$$H1: y = s + n$$

- Two types of error:
  - False alarm:

$$\alpha = P(H1 \mid H0)$$

  - False dismissal:

$$\beta(s) = P(H0 \mid H1)$$

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Signal detection: Optimality

- When s is one known waveform, simple:
  - ››Neyman-Pearson lemma:threshold on likelihood ratio minimizes β for any constraint on α
- Optimality not well defined when s can take values in a subspace W (i.e. when H1 is a *composite* hypothesis):
  - ››Bayesian: assume prior p(s), integrate likelihood over W, back to Neyman-Pearson
    - –Excess power (Anderson et al.)
    - –Excess power #2 (Vicere)
  - ››Average: minimize mean of β(s) over W, for a constraint on α
    - –Time domain filters (Orsay group)
  - ››Minimax: minimize maximum of β(s) over W, for a constraint on α
    - –TFCLUSTERS

Optimal signal detection: coherent vs incoherent

signal subspace known precisely

signal subspace completely unknown

Match filter:

Signal evolution known exactly; gives an optimal rule to weight various data points.

$$\max_{s \in W} \langle y, s \rangle \underset{H_0}{\overset{H_1}{\gtrless}} \eta$$

Total power:

Signal subspace has no structure, and is therefore invariant under rotation ($W = R^N$).

Optimal detector must have same property:

$$|y|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \eta$$

Note:

$$\max_{s \in R^N} \langle y, s \rangle = |y|^2$$

Signal detection vs signal estimation

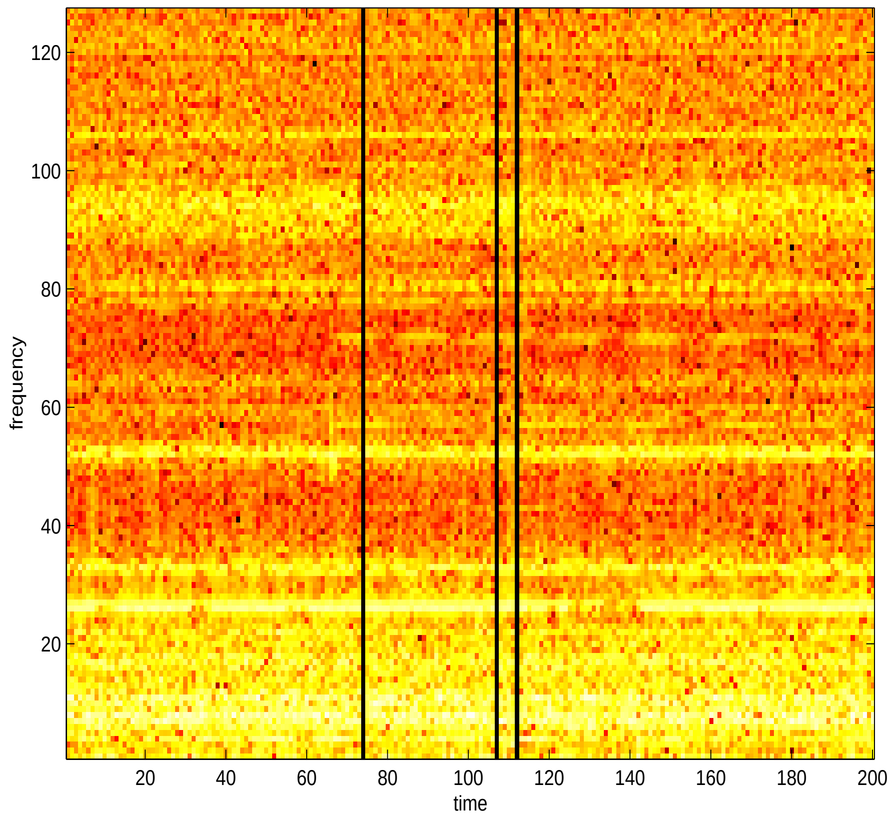
- Interesting link between optimal estimation and optimal detection:

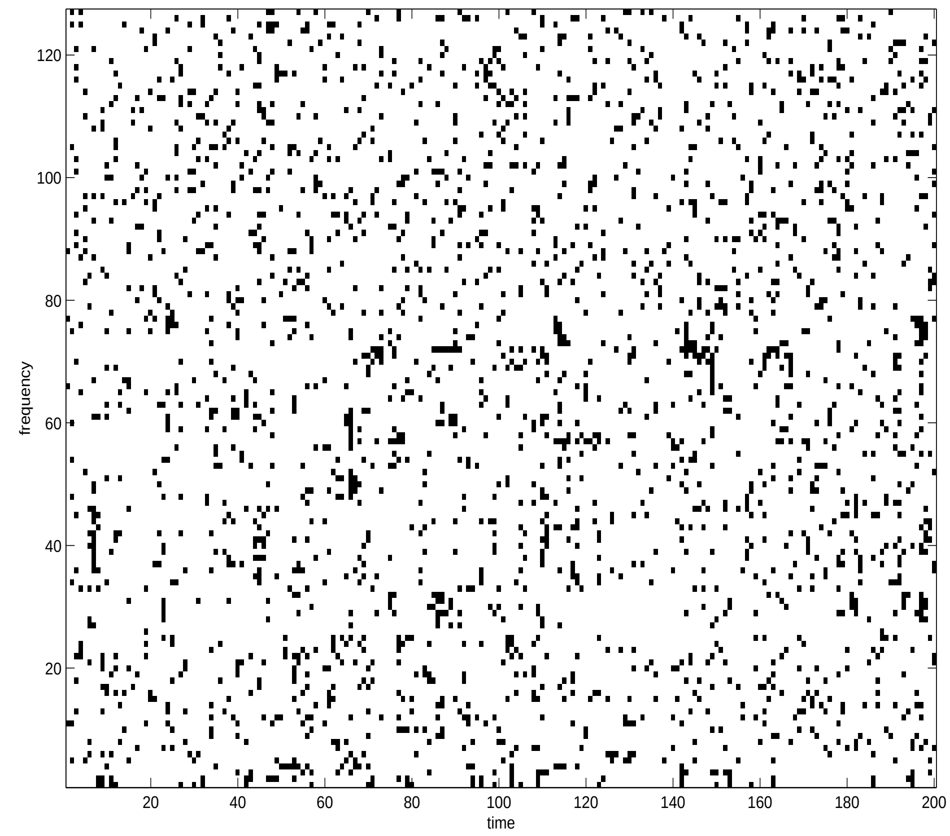
$$\langle y, r \rangle \underset{H_0}{\overset{H_1}{\gtrless}} \eta$$

is the optimal detector if r is the optimal (in mean square) estimator of s.

TFCLUSTERS: first threshold

- compute spectrogram (non-overlapping, no window)
- apply threshold on power; get black pixel probability $p=\exp(-\eta)$





TFCLUSTERS: second threshold

- For some subset of the spectrogram, threshold on the power integrated over all black pixels
- In practice, this is equivalent to computing

$$\langle y, r \rangle$$

with r defined as

$$\tilde{r}_{ij} = \begin{cases} \tilde{y}_{ij} & \text{if } |\tilde{y}_{ij}| > \eta^{1/2} \\ 0 & \text{otherwise} \end{cases}$$

- This estimator r is minimax optimal in mean square over signals with a sparse spectrogram representation

(Donoho, D. L., IEEE Trans. Inf. Theory **41**, 613)

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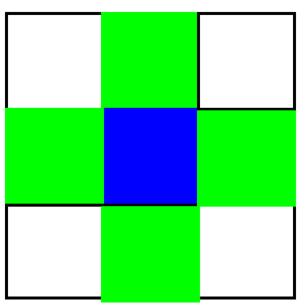
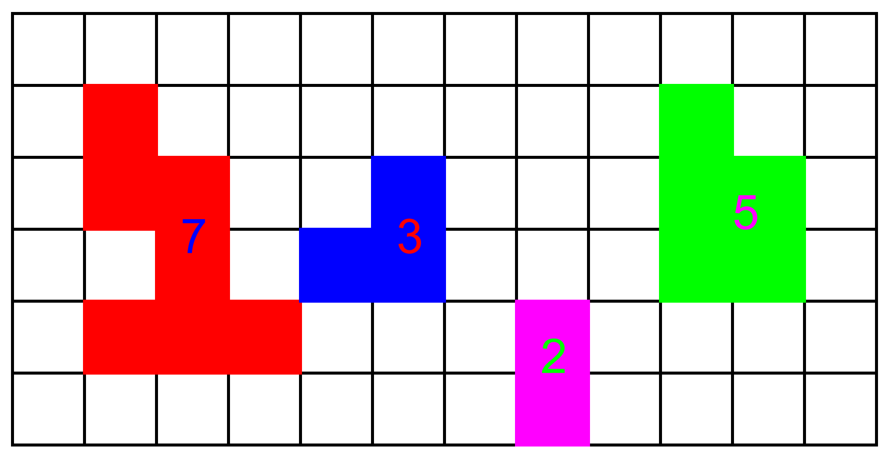
TFCLUSTERS: clustering analysis

What do burst signals look like in the spectrogram?

- short signals (Δt << 1 / bandwidth) have power spread over all frequencies (Heisenberg principle)
- longer signals have many tens or hundreds of cycles. If the frequency is determined by rotation, it can't change too rapidly

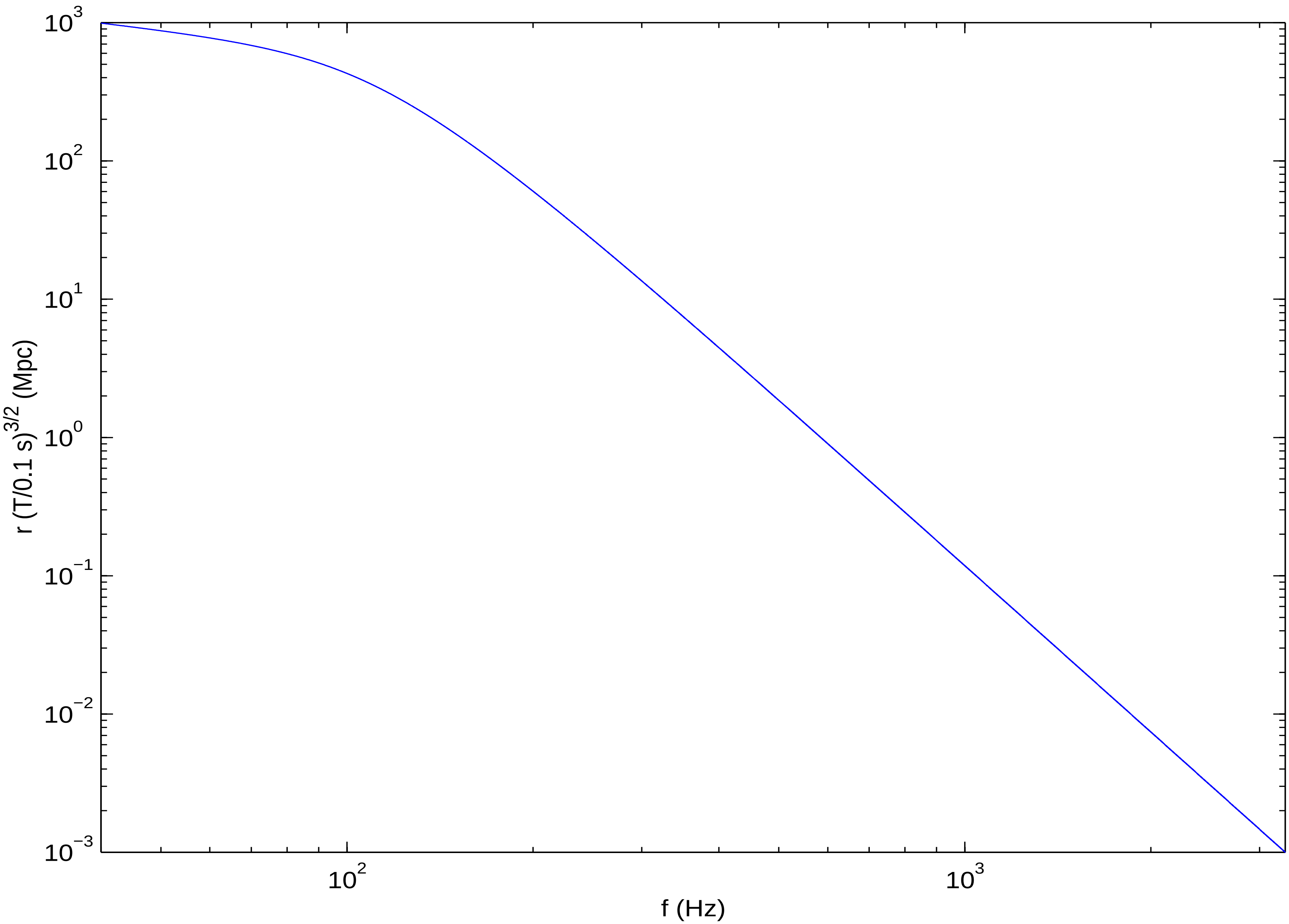
››The amound of angular momentum radiated by gravity waves is related to the energy flux. For a certain strain h, there's a maximum distance such that $\Delta J / J < 1 / T f$





TFCLUSTERS: clustering analysis

maximum distance at which rotation dominated sources certainly form clusters, for LIGO-I 4k



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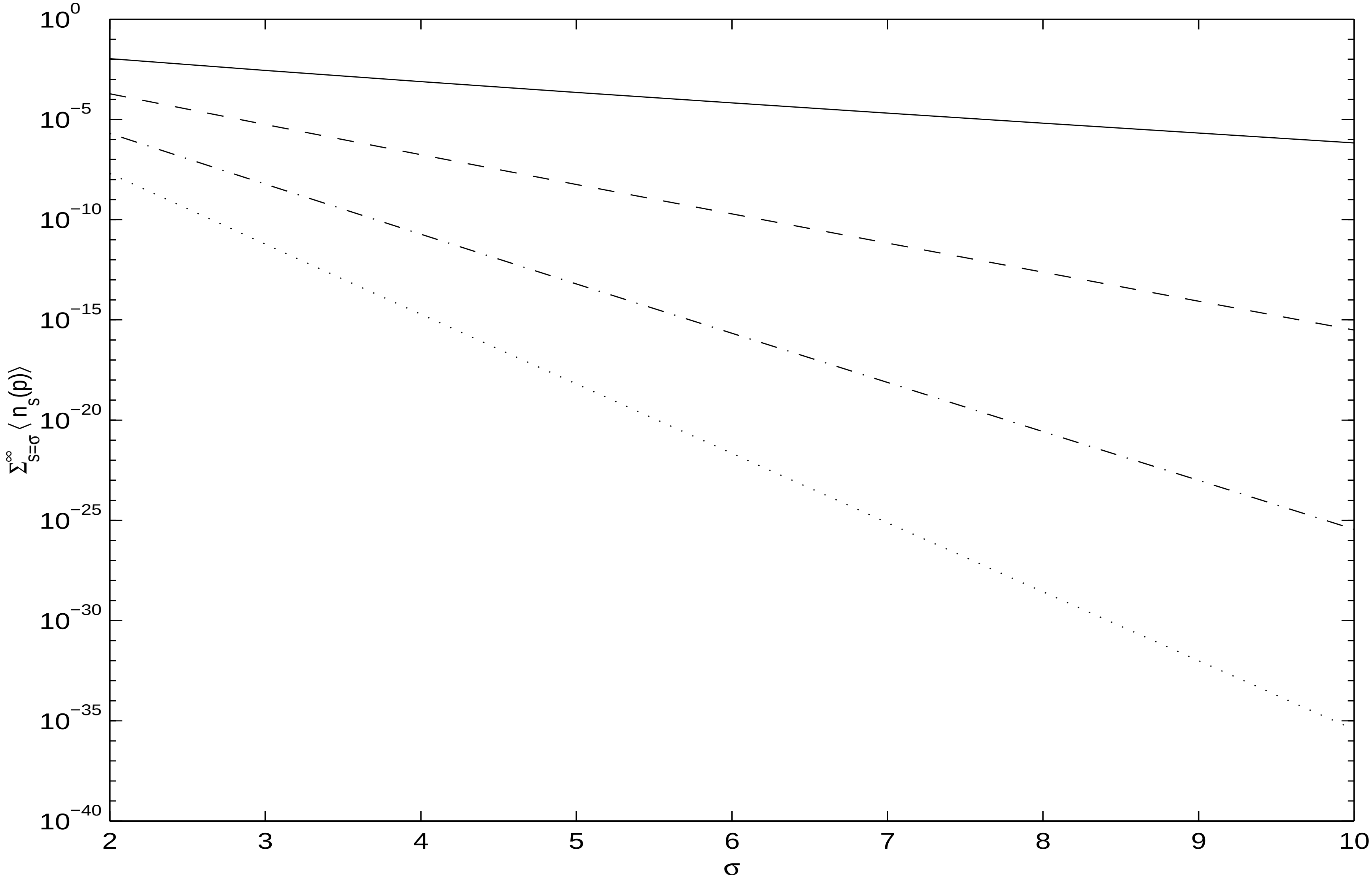
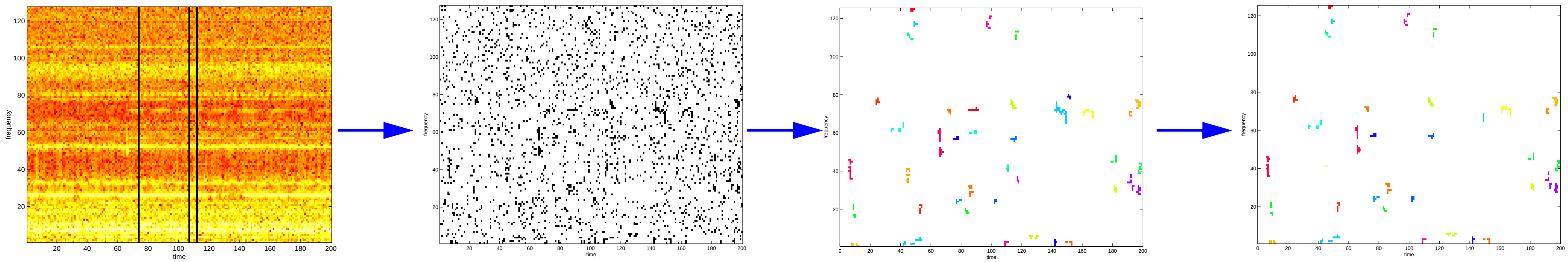
TFCLUSTERS: clustering analysis

mean number per pixel of clusters of size s > sigma



TFCLUSTERS: algorithm



construct spectrogram → first power threshold → clustering analysis → threshold on integrated power

time resolution
whitening filter

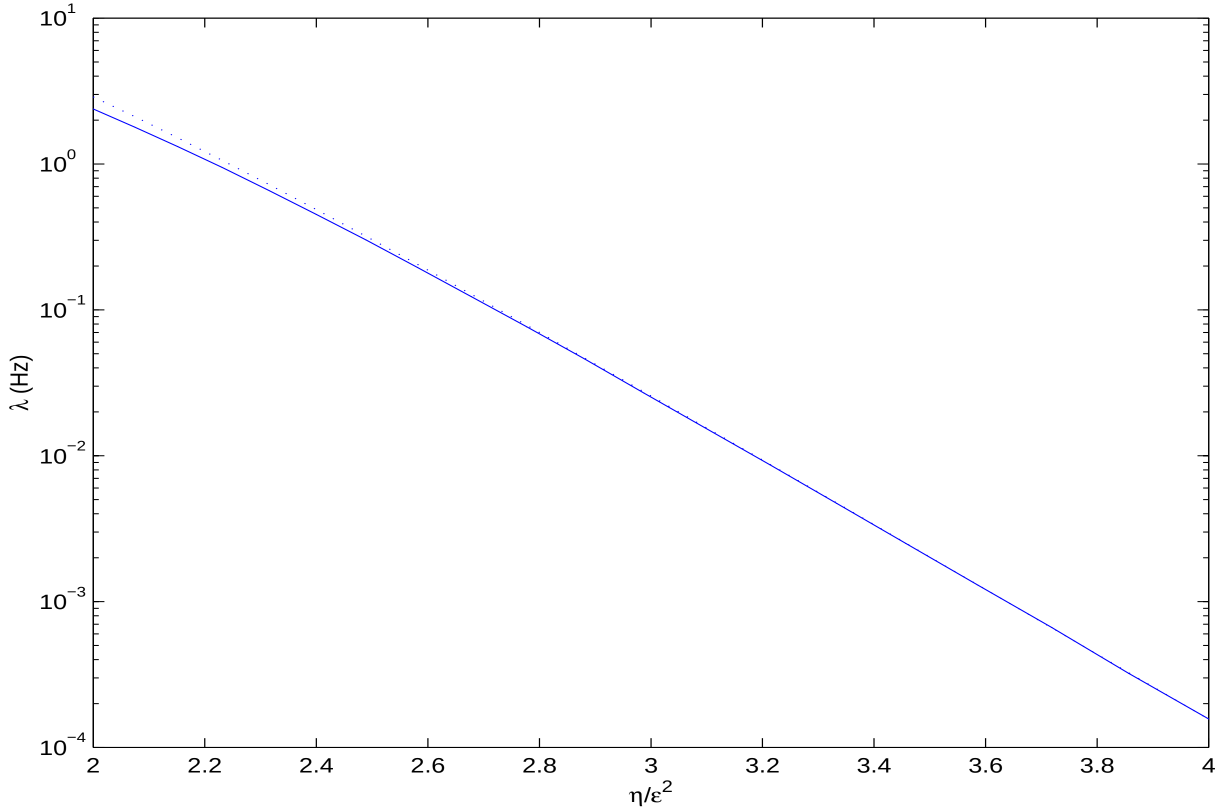
black pixel probability
noise model

minimum cluster size
distance thresholds

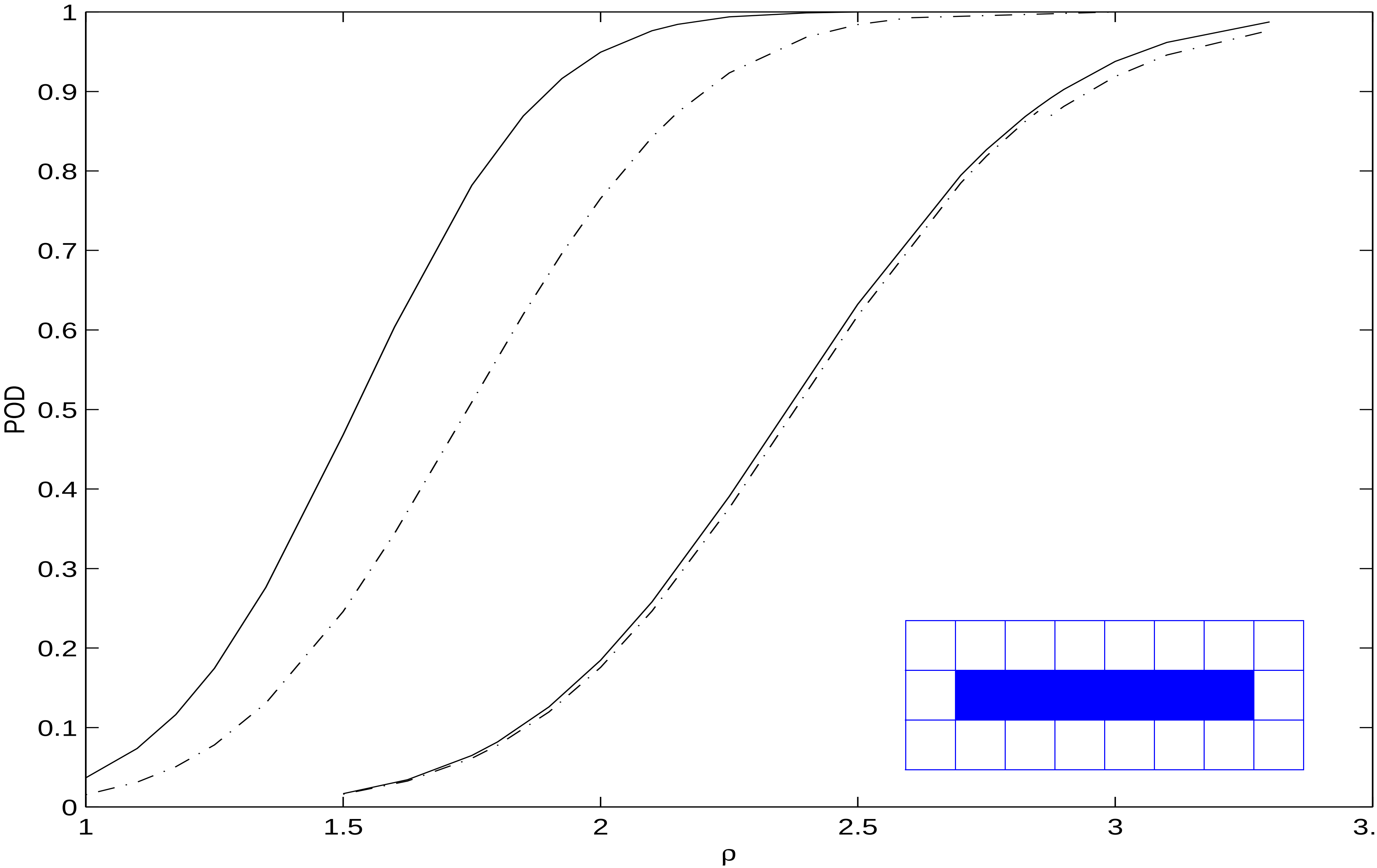
threshold type
threshold

TFCLUSTERS: operating characteristics

- likely to be optimal or near optimal in the minimax sense for signals forming small clusters in the spectrogram
- false alarm rate completely understood in Gaussian noise
- with much work, can also compute efficiency for specific signals



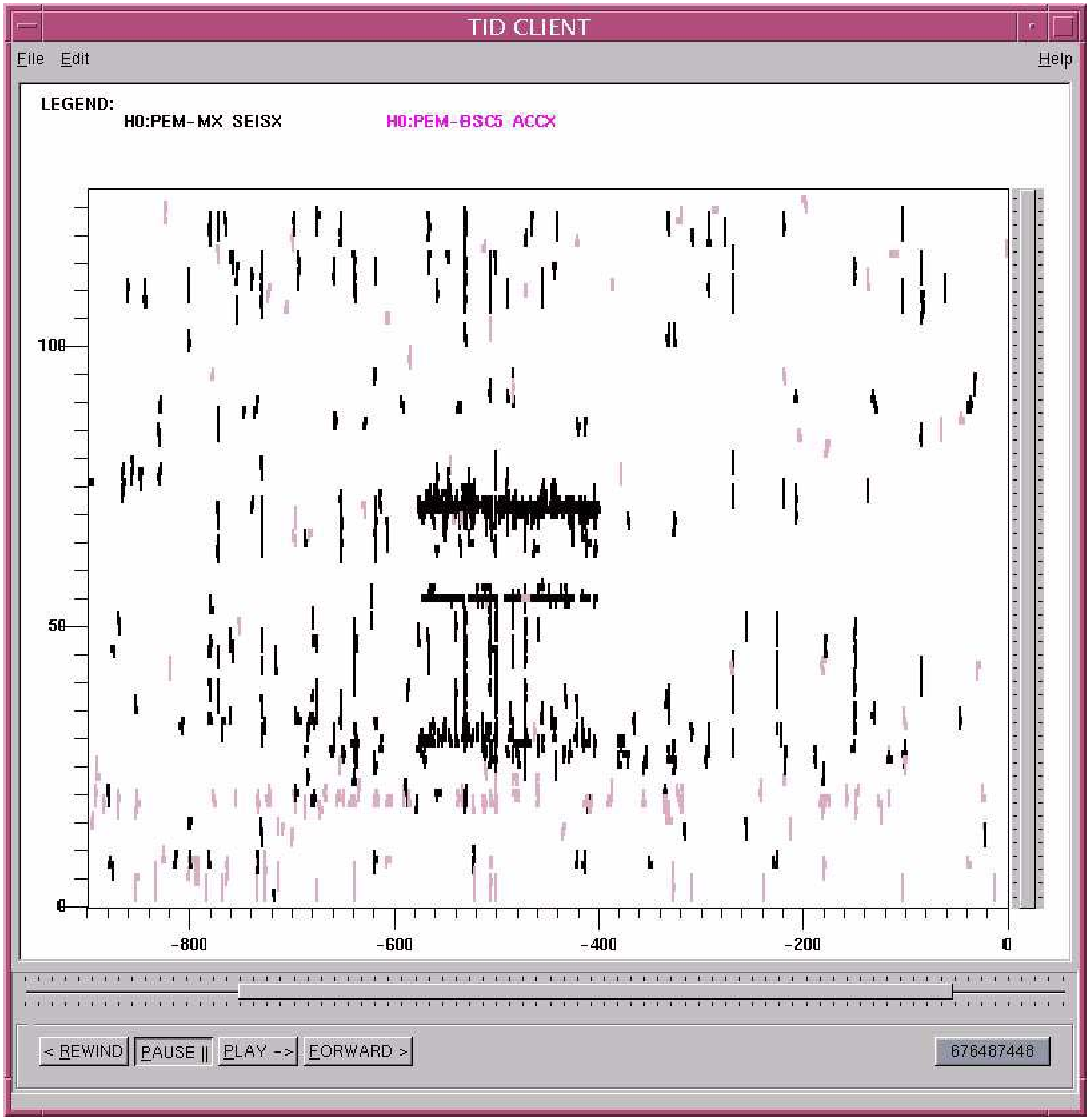
TFCLUSTERS: operating characteristics



TFCLUSTERS: real world

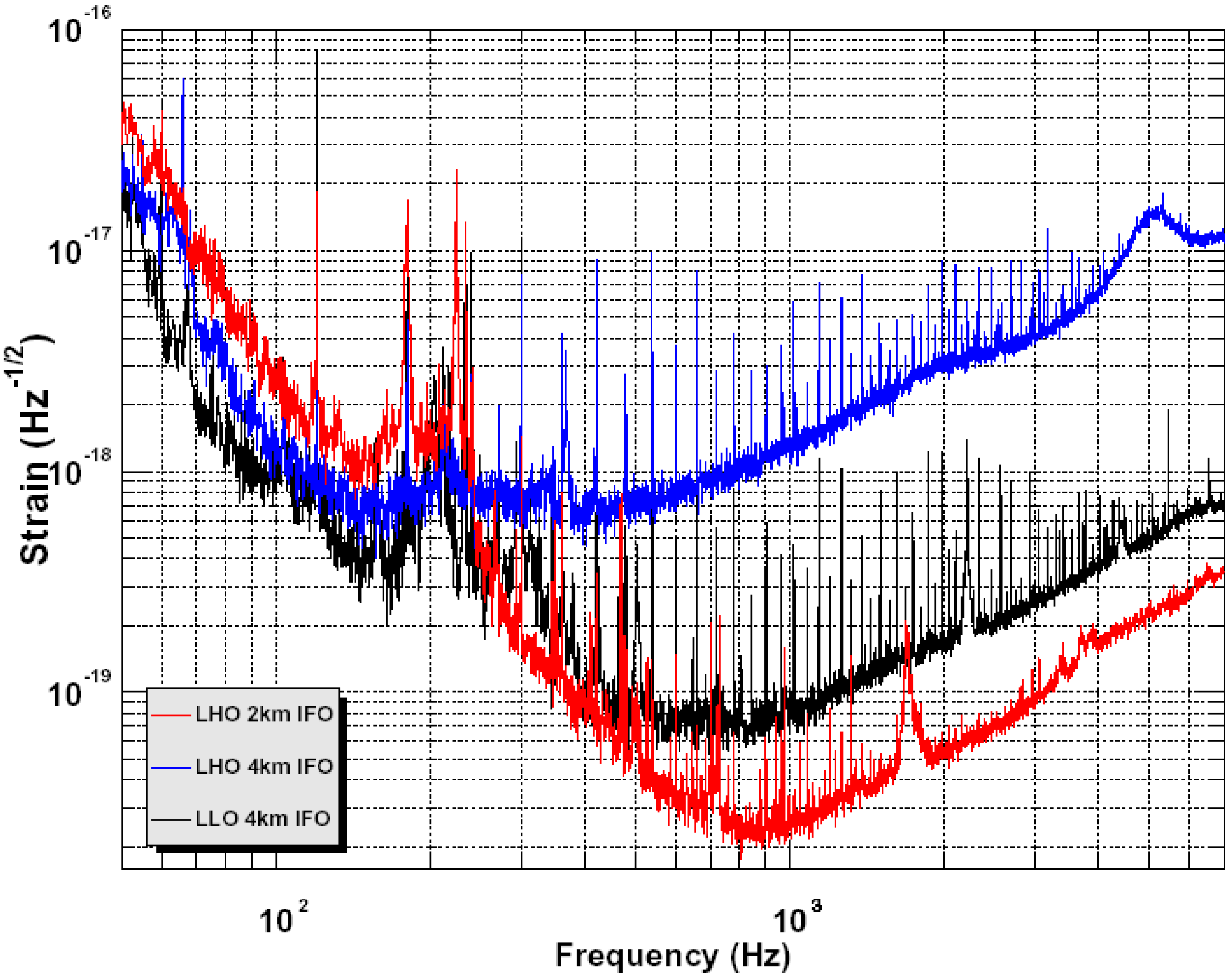
- runs at 250-500x real-time (most expensive task is cluster identification)
- rough whitening important, especially at low frequencies
- actual implementation models background power distribution with a Rice distribution
- LDAS & DMT implementations

TFCLUSTERS: DMT implementation



E7

- 18 days, 160 hours of coincident operation for H2 and L1



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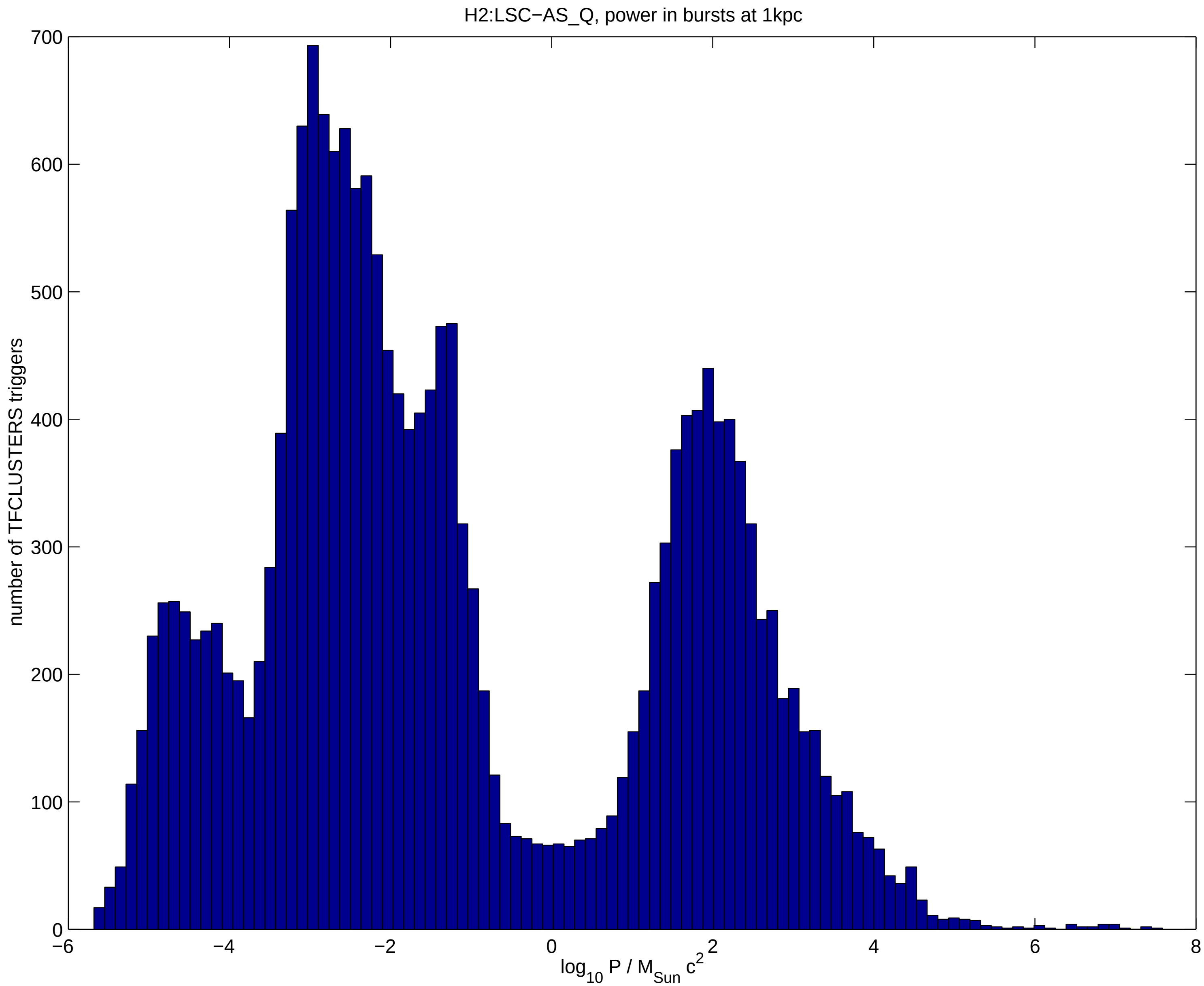
H2 bursts



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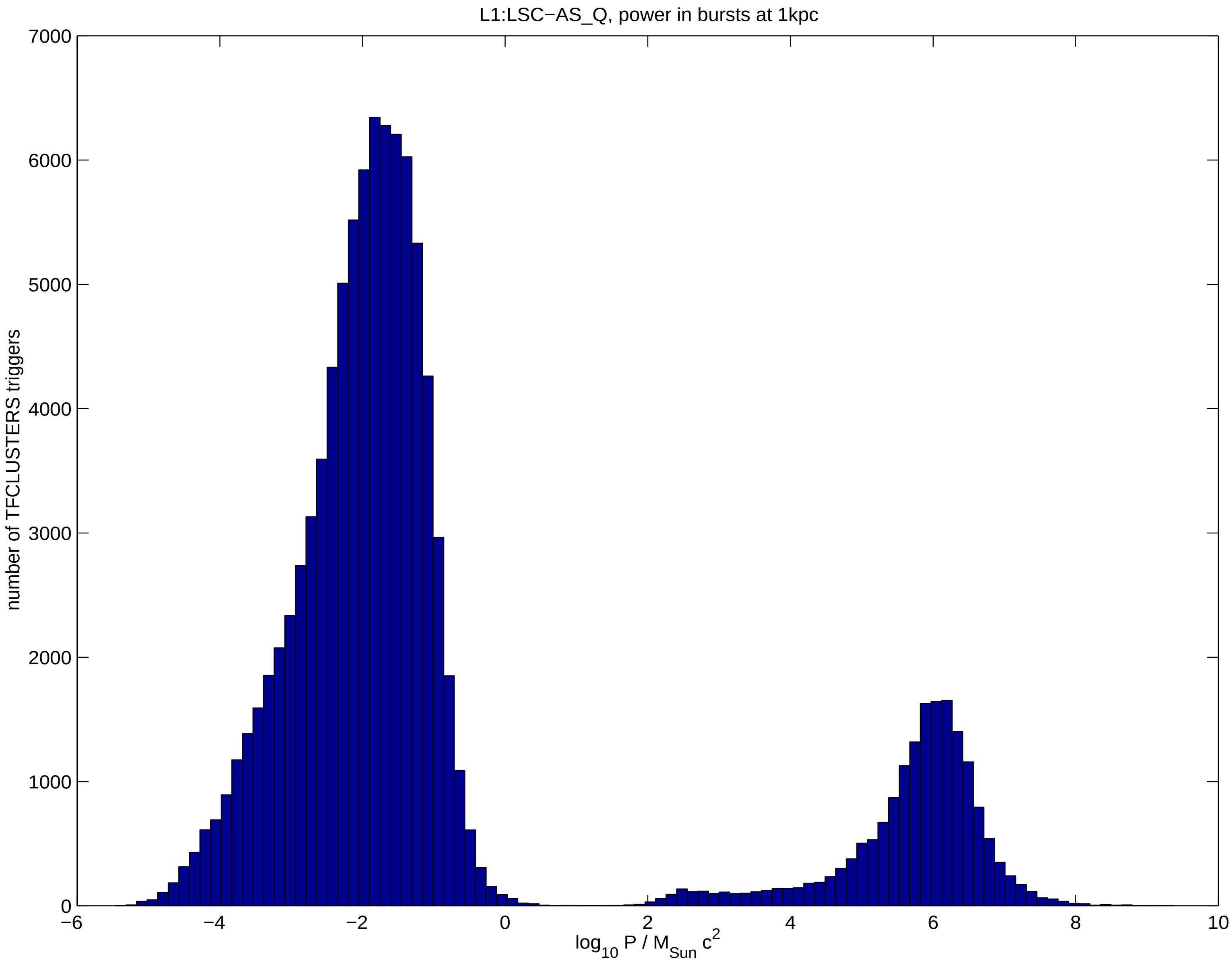
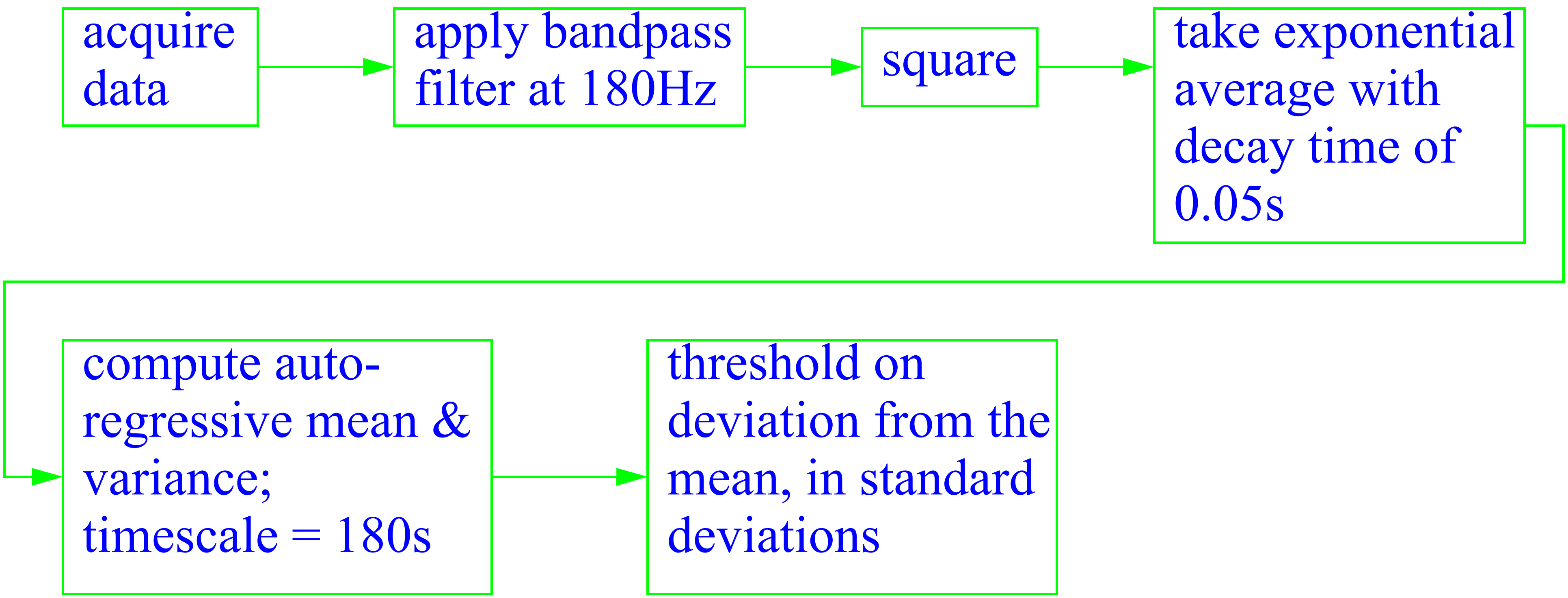
L1 bursts



L1:LSC−AS_Q, power in bursts at 1kpc
number of TFCLUSTERS triggers
7000
6000
5000
4000
3000
2000
1000
0
−6
−4
−2
0
2
4
6
8
10
log10 P / MSun c2

MICH_CTRL veto on H2

- it was found that MICH_CTRL could be used to predict glitches in AS_Q
- found using time series analysis near TFCLUSTERS triggers that 3rd power line harmonic was a good predictor
- use GIDE DMT monitor:



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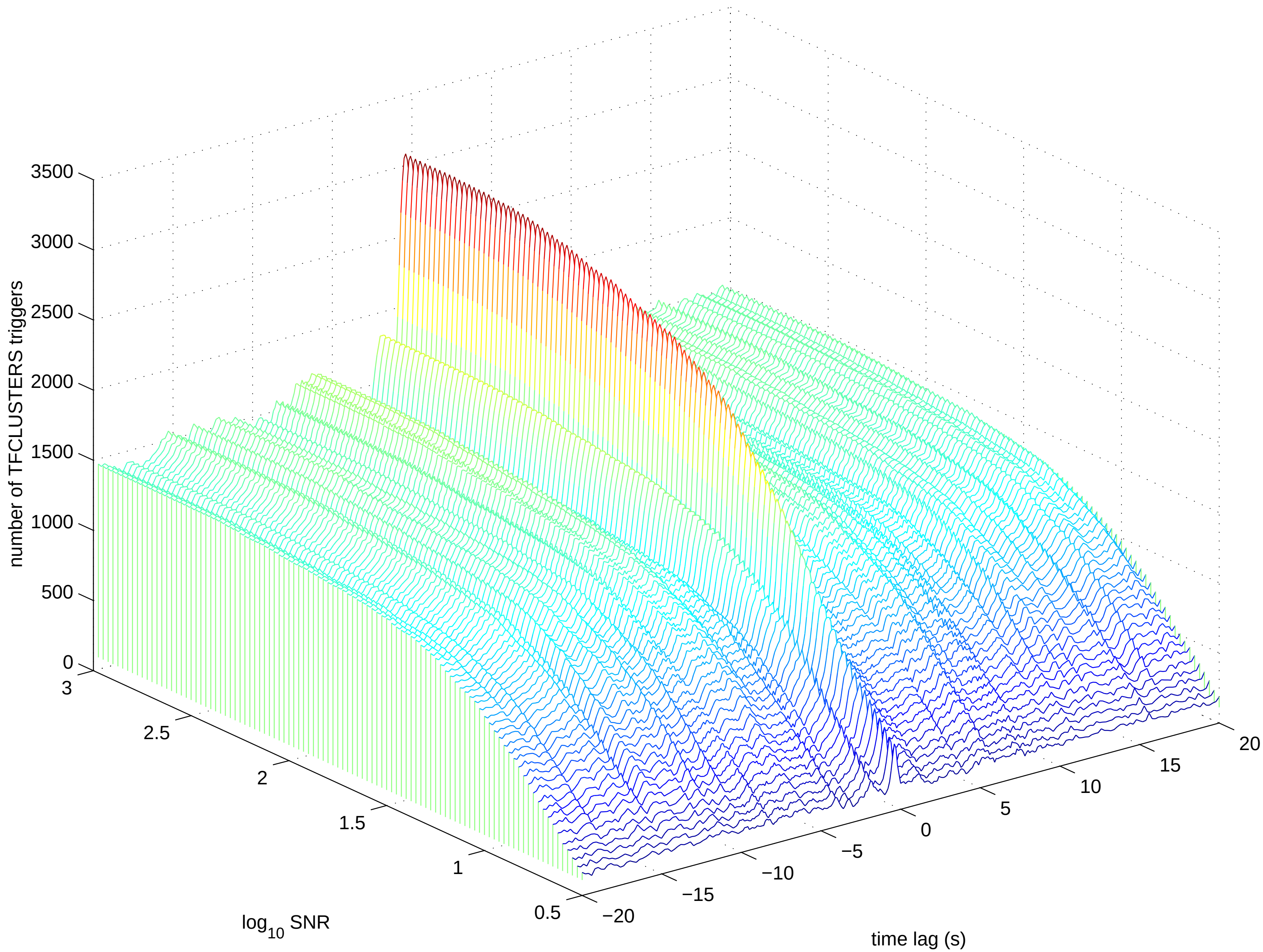
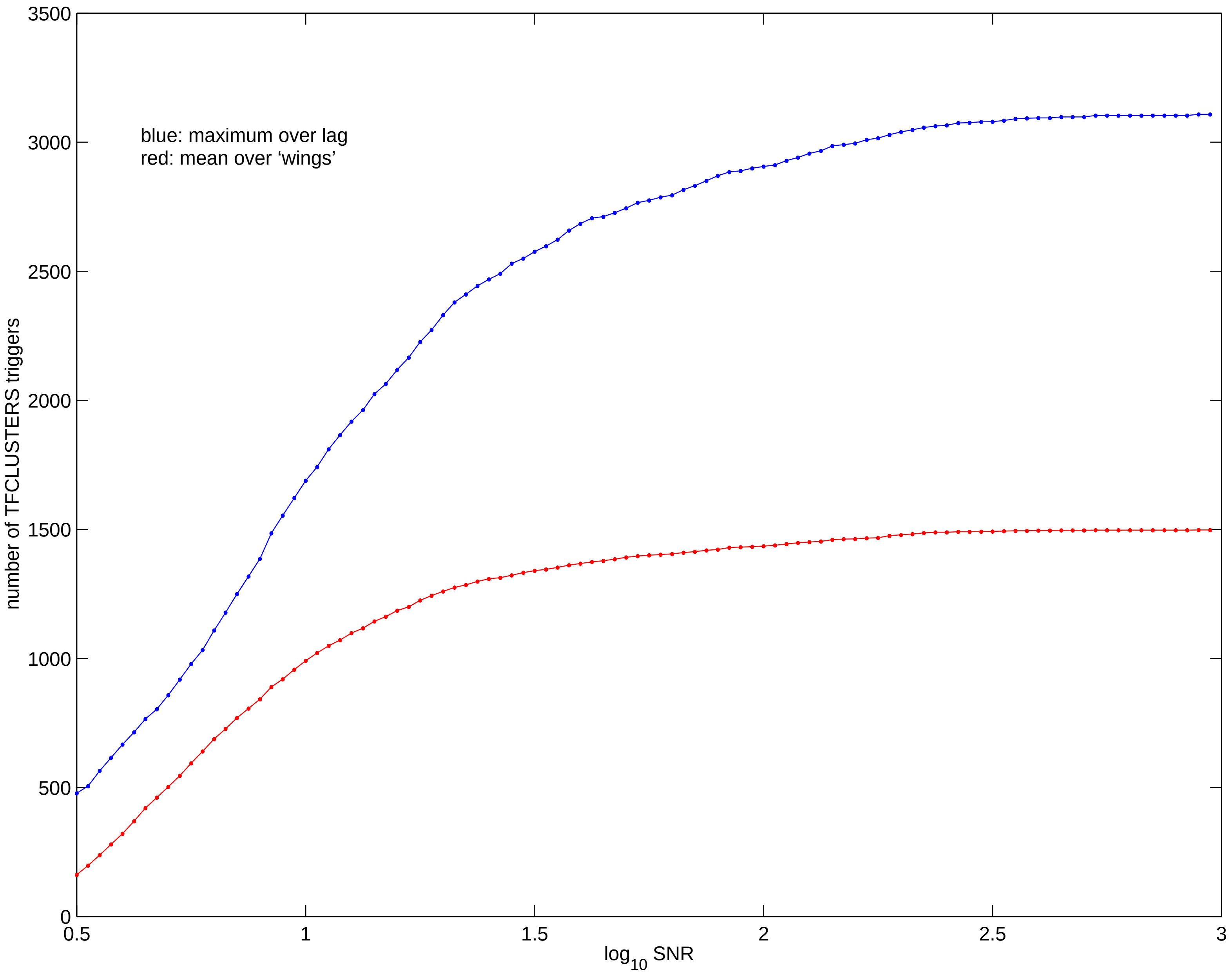
MICH_CTRL veto: efficiency

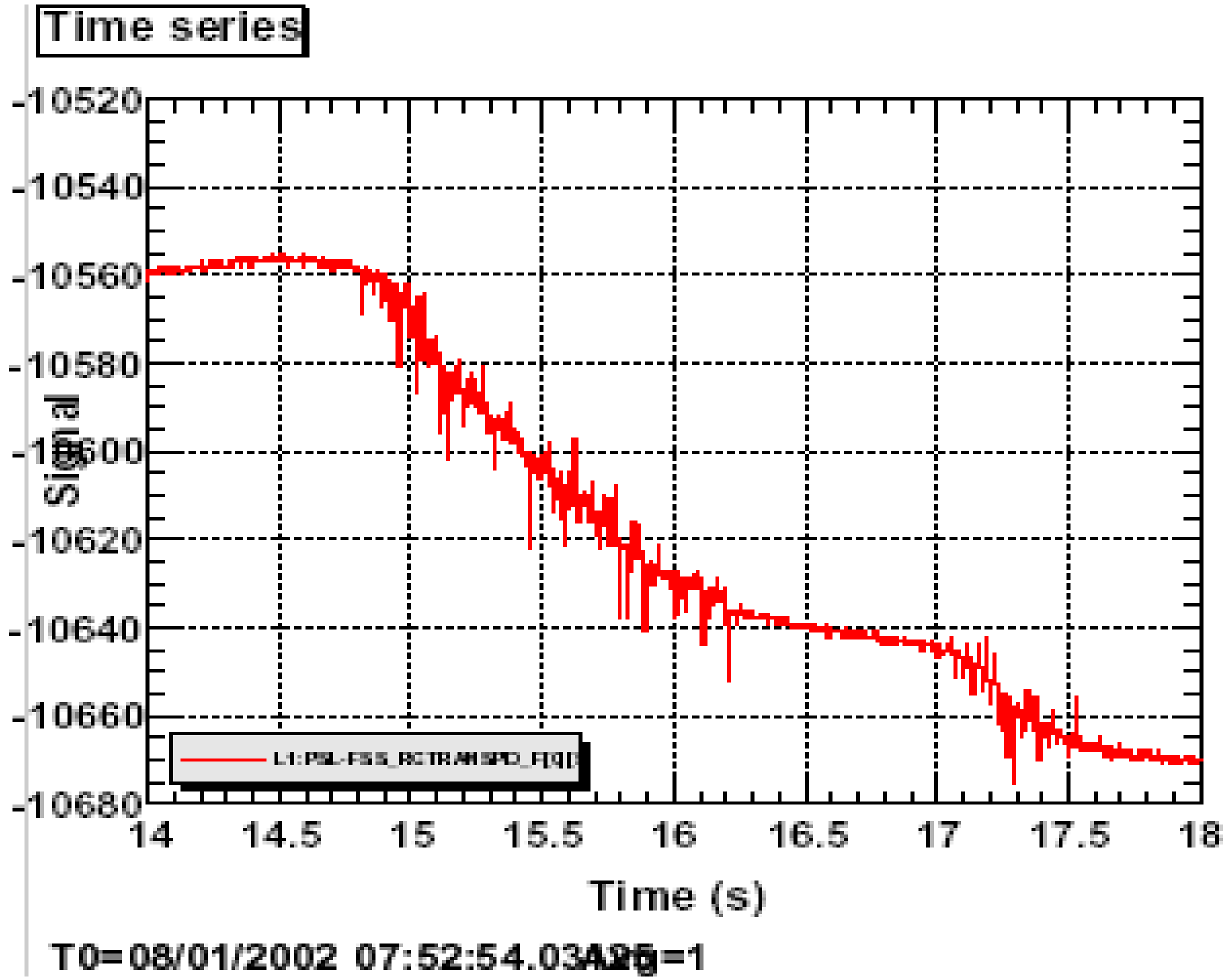


MICH_CTRL veto: efficiency

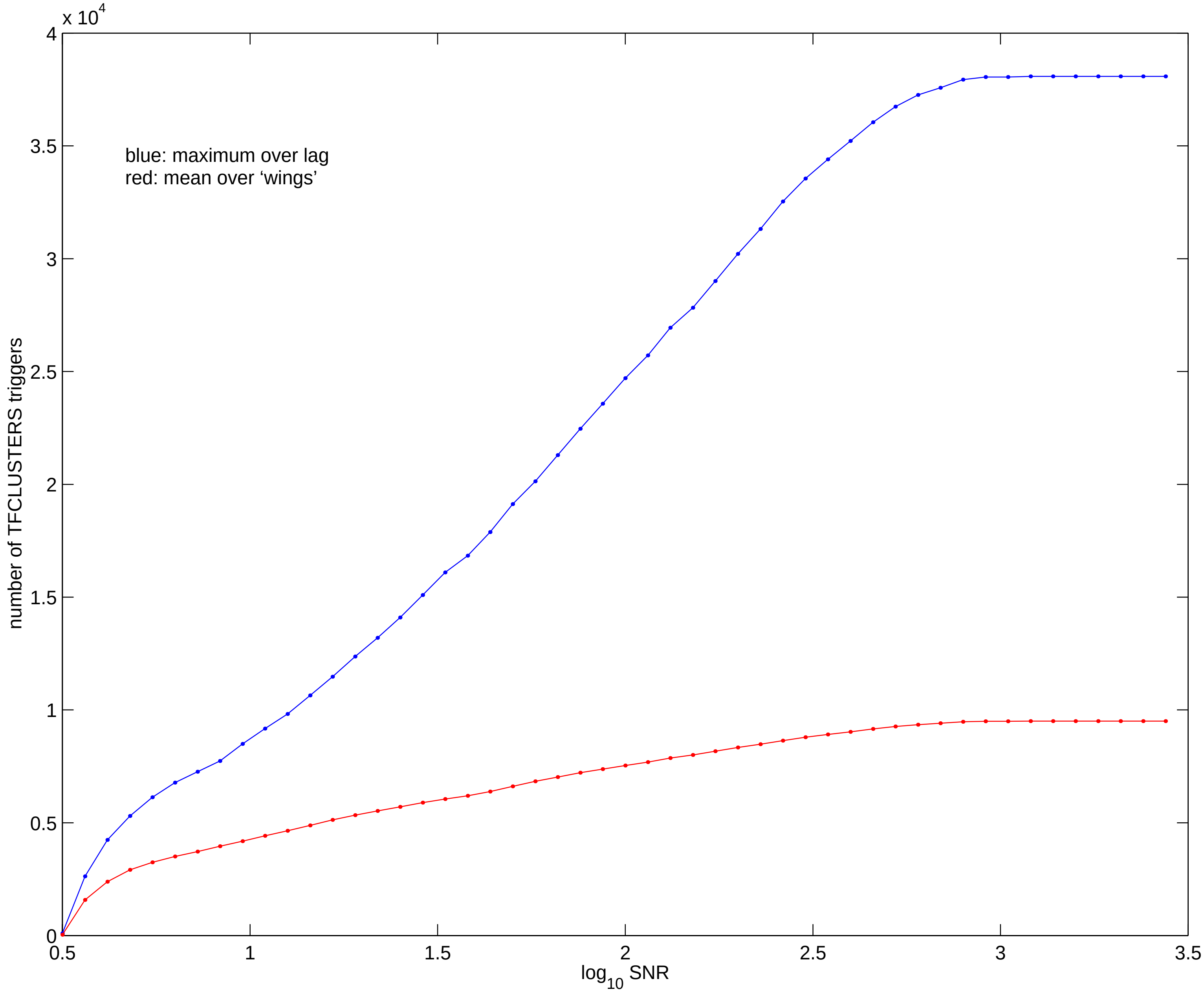


PSL glitch veto on L1

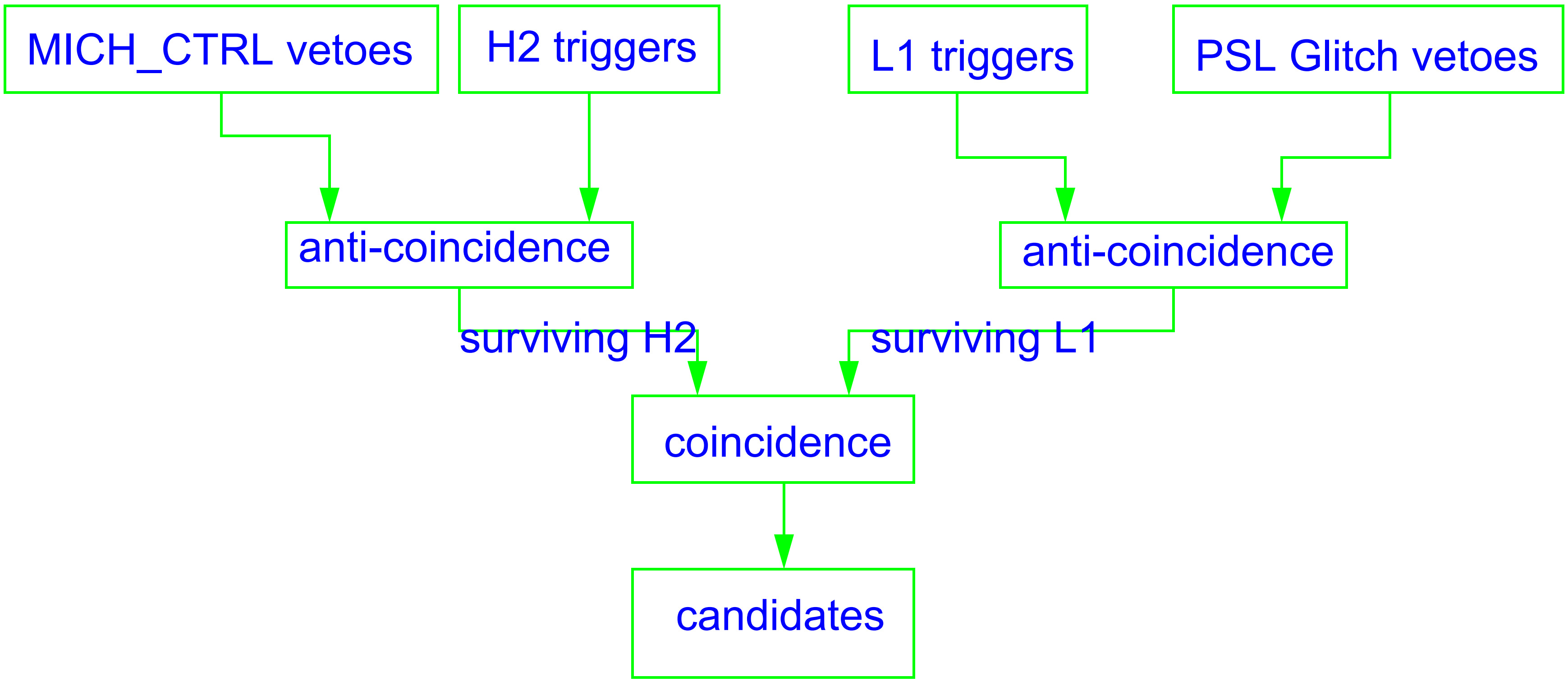
- PSL signal FSS_RCTRANSPD_F has short episodes of excess noise that correlate with glitches in L1:LSC-AS_Q
- use GIDE with a high-pass filter with corner frequency at 20Hz



PSL Glitch veto: efficiency



Toy analysis pipeline



Analysis pipeline

- many variables: thresholds on GW and veto channels, coincidence windows, etc.
- analysis performed on two disjoint data sets:
  - ›› 'Playground' data to setup pipeline variables
  - ›› 'Reserved' data to compute upper limit

Analysis pipeline

- use playground data to optimize expected upper limit
  - ››choose values of pipeline variables
  - ››compute number of coincidences in playground data
  - ››compute livetime
  - ››estimate background rate λ from number of coincidences
  - ››extrapolate livetime T to reserved data set
  - ››compute expected upper limit:

$$\overline{UL} = \sum_{k=0}^{\infty} \frac{(\lambda T)^k e^{-\lambda T}}{k!} UL(k;\alpha, \lambda, T)$$

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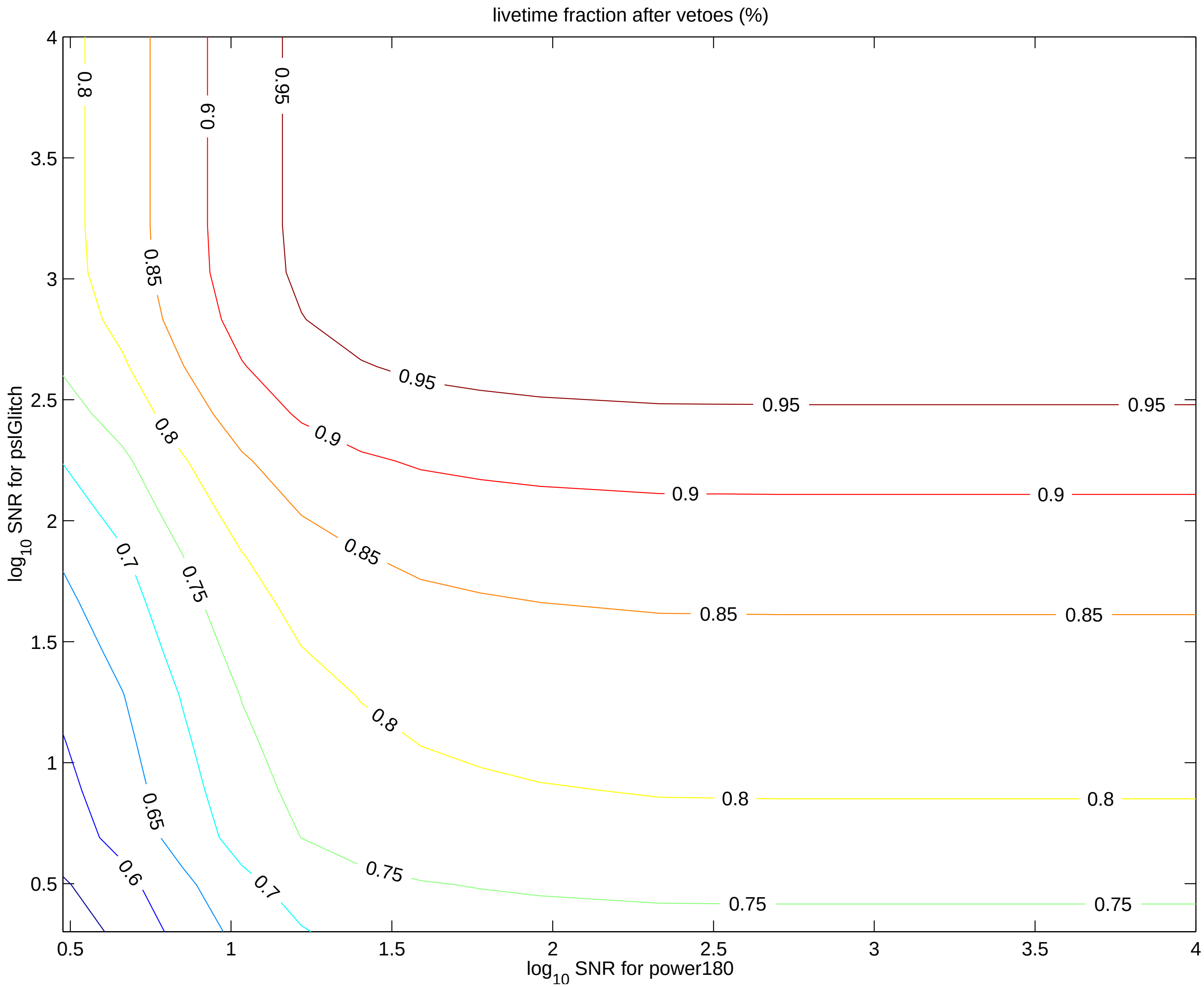
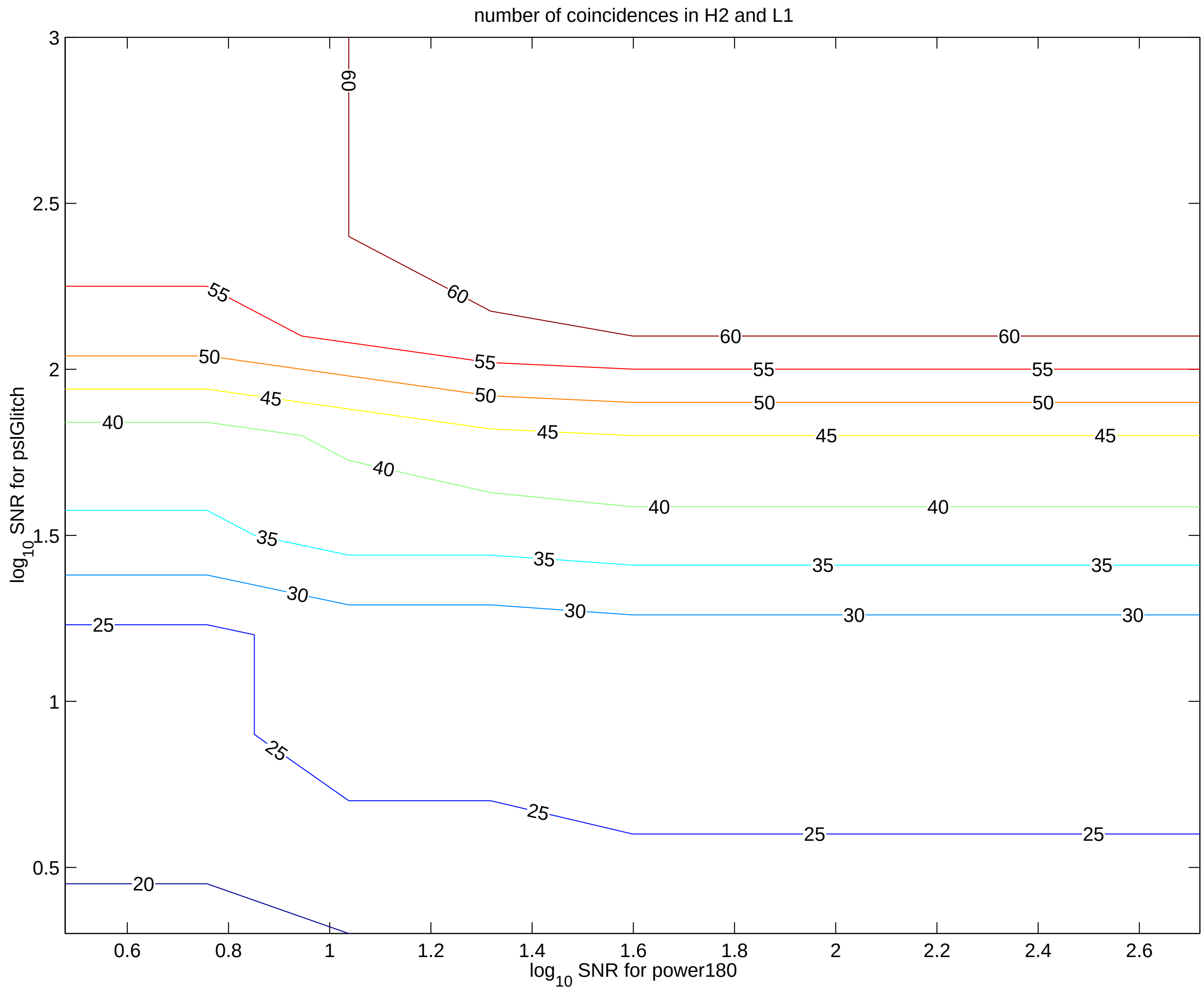
Livetime


livetime fraction after vetoes (%)
log10 SNR for psIGlitch
log10 SNR for power180
0.5
1
1.5
2
2.5
3
3.5
4
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

Background



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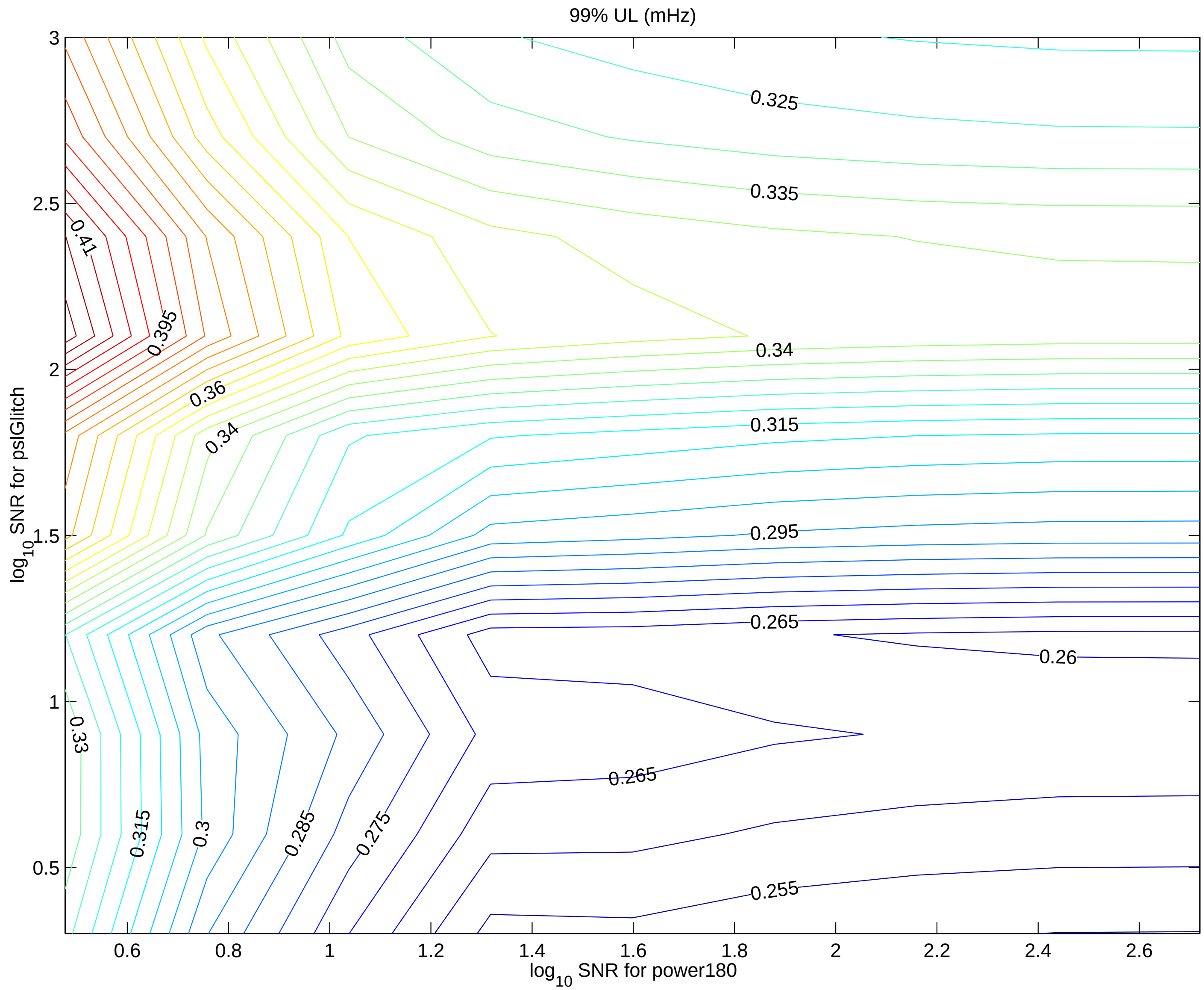
Projected upper limit



Todo list

- need sensitivity (i.e. probability of detection ‘averaged’ over all possible bursts) to turn UL into astrophysical statement
- repeat procedure for more vetoes, i.e. optimize over higher dimensionality space