Trigger Algorithms for the SuperCDMS Dark Matter Search

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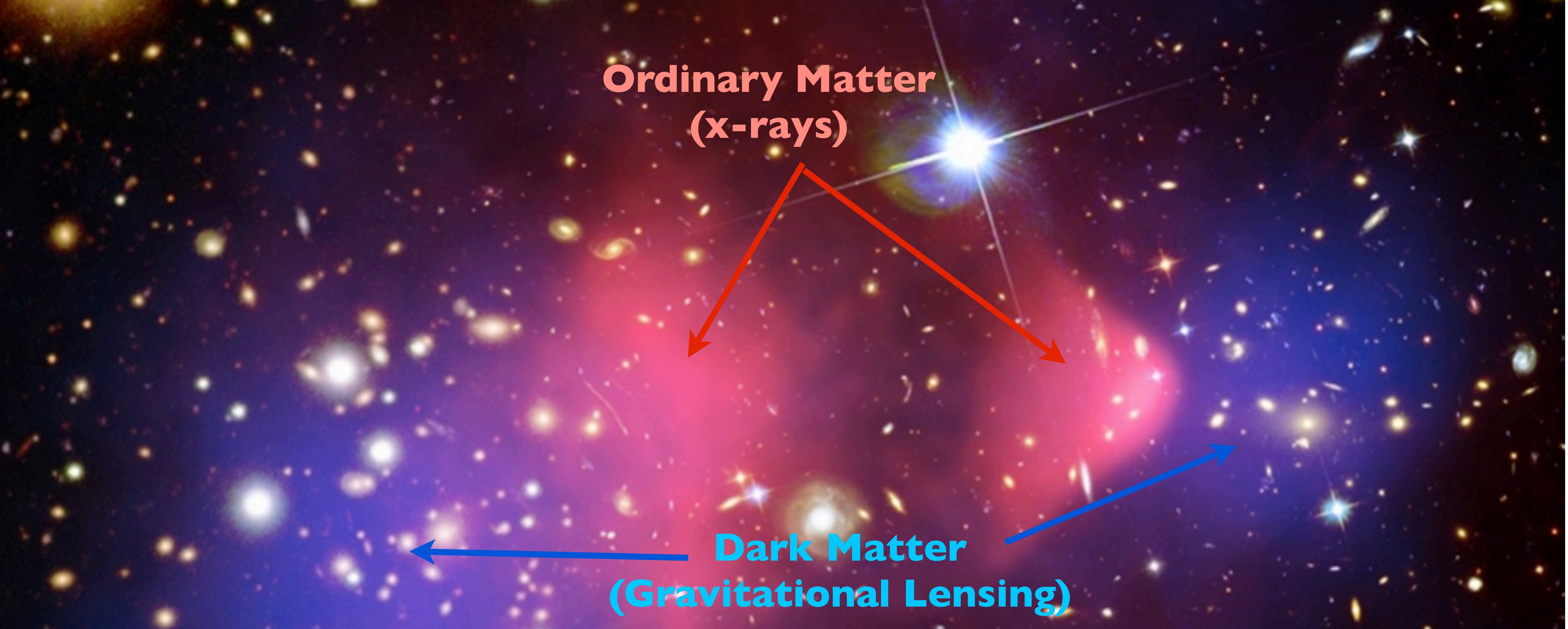
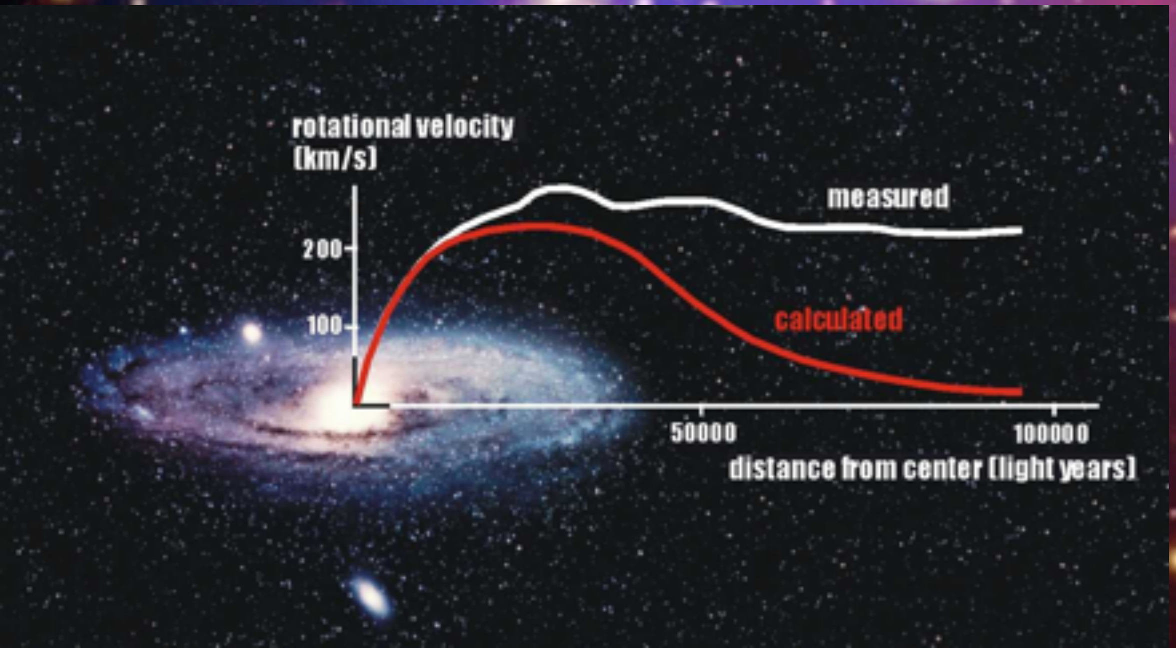
Outline

- Introduction: dark matter and the CDMS experiment
- Triggering during data-taking: Sensitivity of box-car filters, bandpass filters and optimal filters
- Performance Comparison: which is better and why
- What happens if the noise changes during data-taking with the experiment ?
- Conclusions

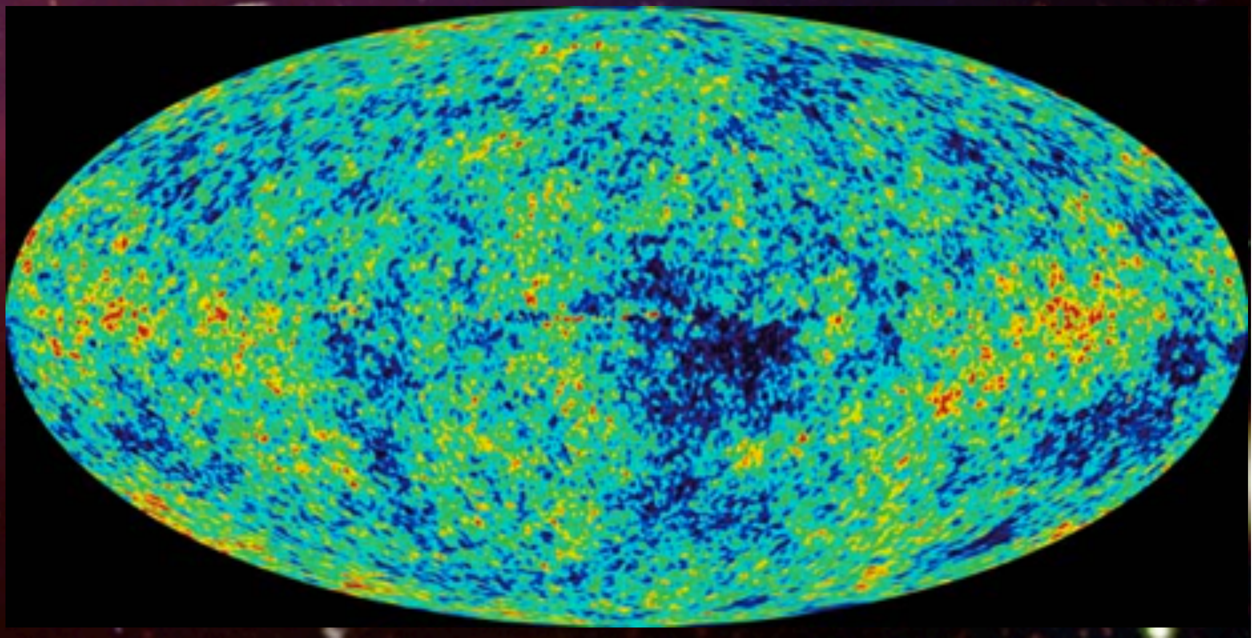
Evidence For Dark Matter



Galactic Rotation Curves

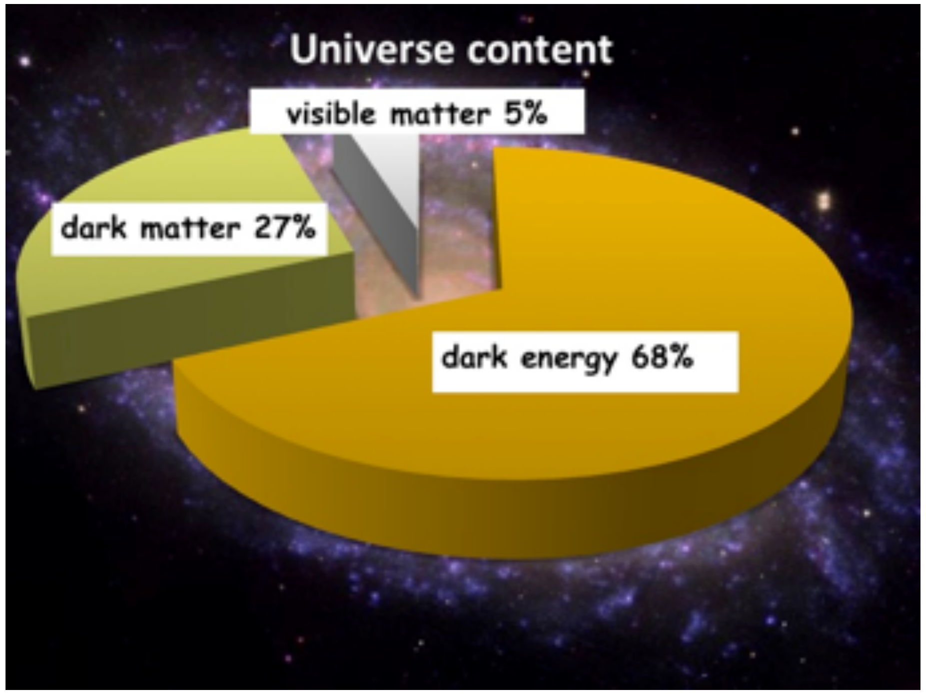


Cosmic Microwave Background



Is Dark Matter a Particle?

The Bullet Cluster suggests that dark matter may be a <u>particle</u>

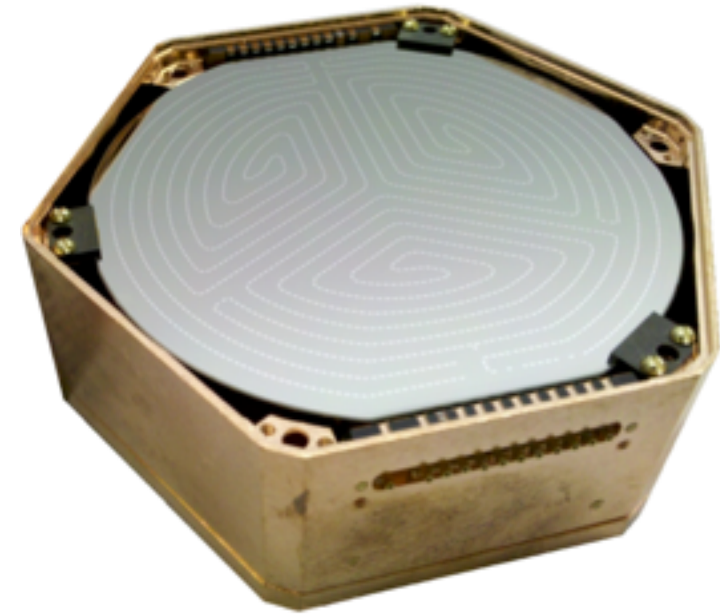


Dark Matter Particle Candidate:

- WIMPs (Weakly Interacting Massive Particles)
- Axion
- SuperWIMPs
- Sterile neutrinos
- Neutralinos
- Gravitino
- ....

Hunt for Dark Matter

CDMS, XENON, LUX ...



Direct Detection

AMS, FERMI...

Indirect Detection

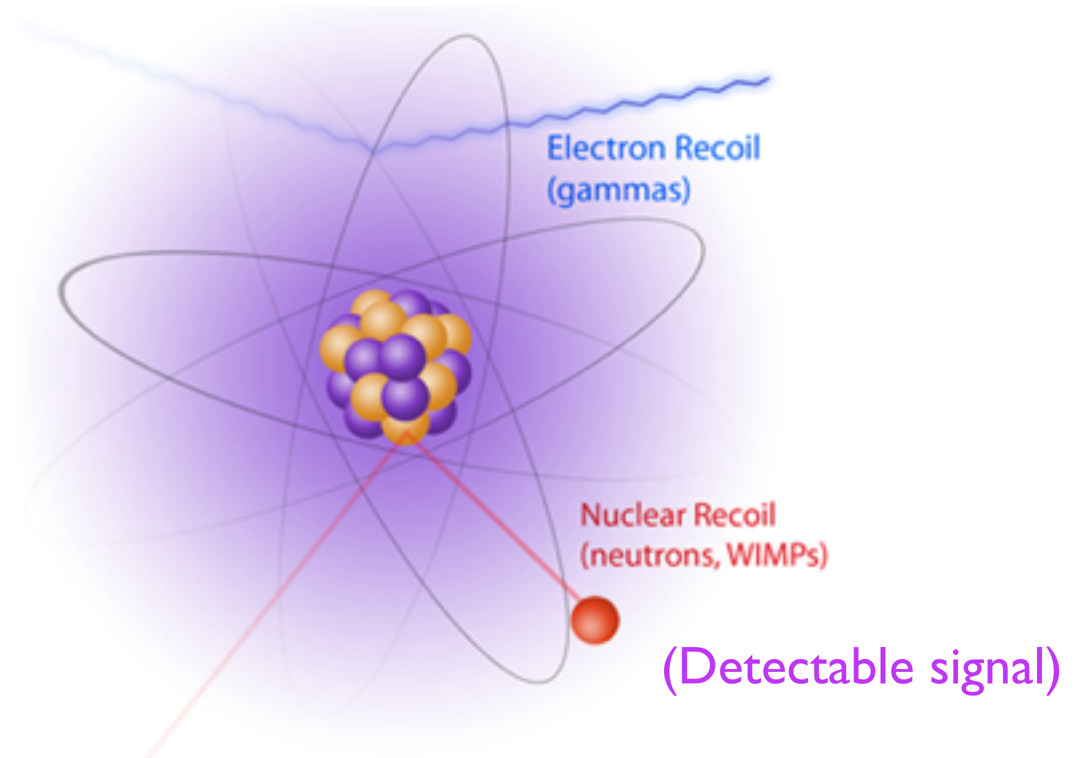
Production in Collider

Atlas, CMS...

Direct Detection of WIMPs

Elastic Scattering of WIMPs off target
➜ nuclear recoil

Background (gamma and beta particles) interact with the atomic electrons
➜ electronic recoil

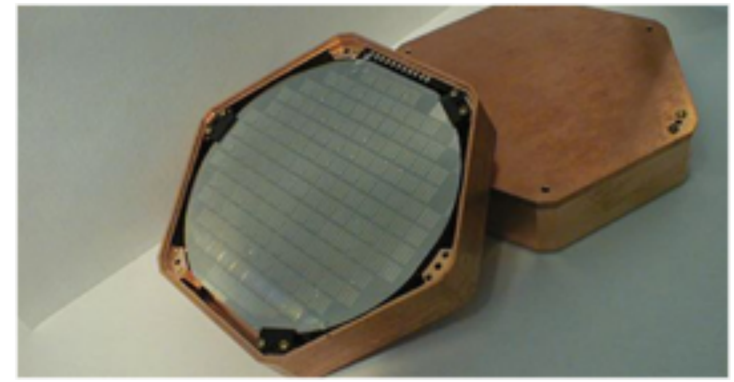


Requirements for WIMPs detectors:

- Large target mass
- Low energy threshold
- Ultra-low background
- Nuclear and electronic recoil discrimination

CDMS Experiment Idea

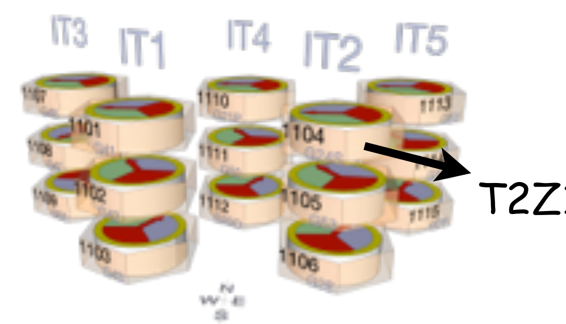
1) Make a detector out of a material with which the WIMPs can interact (in CDMS Ge and Si).
CDMS=Cryogenic Dark Matter Search



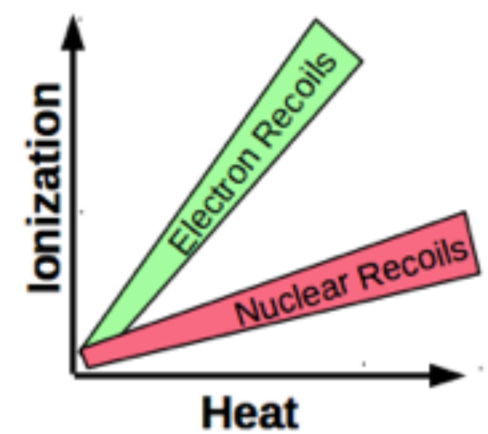
Crystals: Ge, Si
cooled to few mK
- low heat capacity

2) Determine when the interaction occurs and measure the amount of charge and heat

5 towers * 3 detector each
= 15 detectors total



Good discrimination

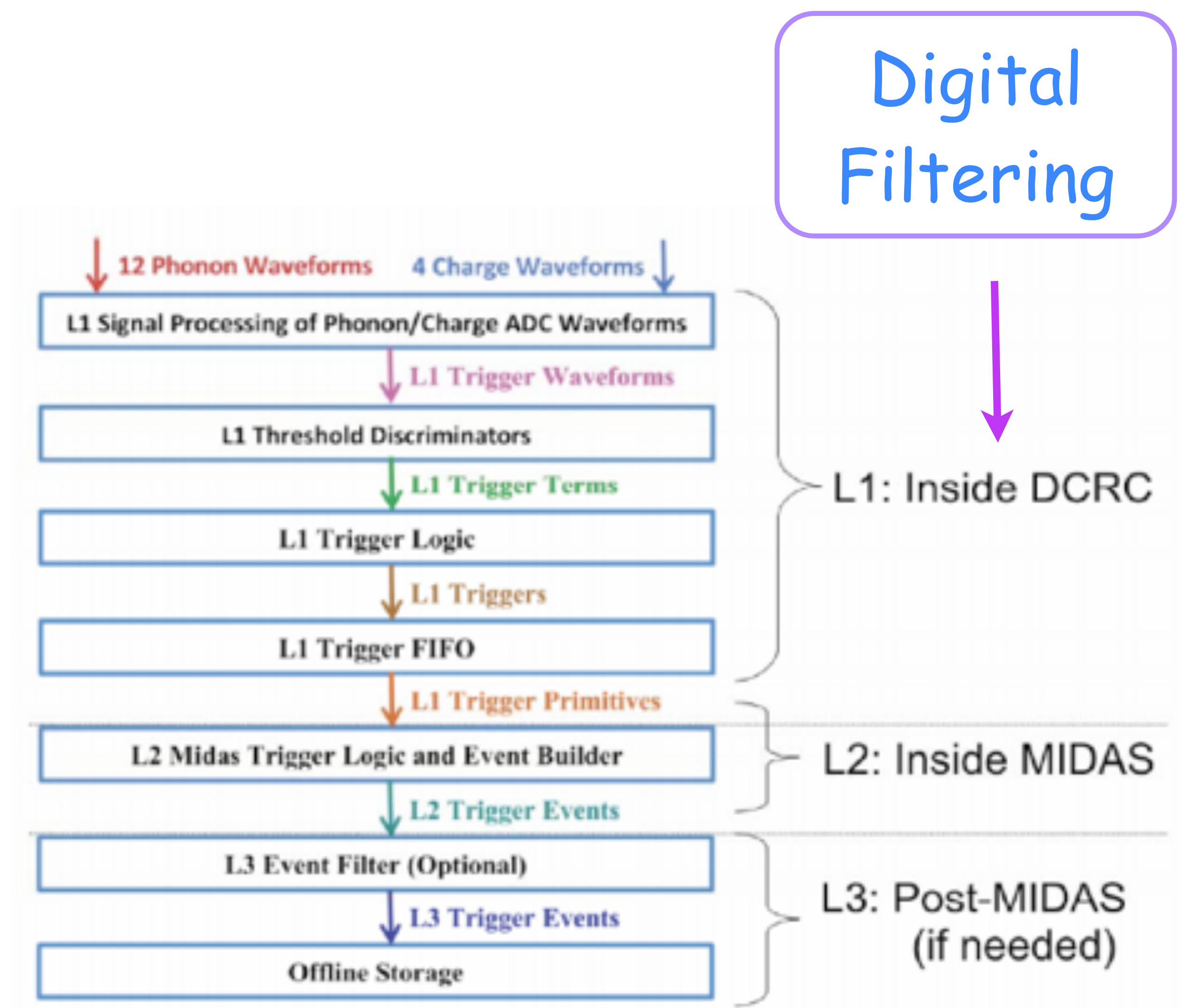


3) Reject background events:
For every potential WIMP interaction there are ≳ 1000 events from unwanted background sources.
(Detector is in deep underground to prevent cosmic background)
@Soudan Lab, Minnesota → later: SNOLAB with better readout electronics

Trigger System

(for the new CDMS Experiment being built now to be installed in the SNOLAB mine)

- Trigger will be made of three systems: L1, L2, L3 (designed to take data in real time from the detector and only write out information for real energy deposits in the detector)
- New Level 1 triggers allows for digital filtering of information directly out of the detectors
- We are exploring different strategies for our filter design in L1



Why the Filter Design is Important

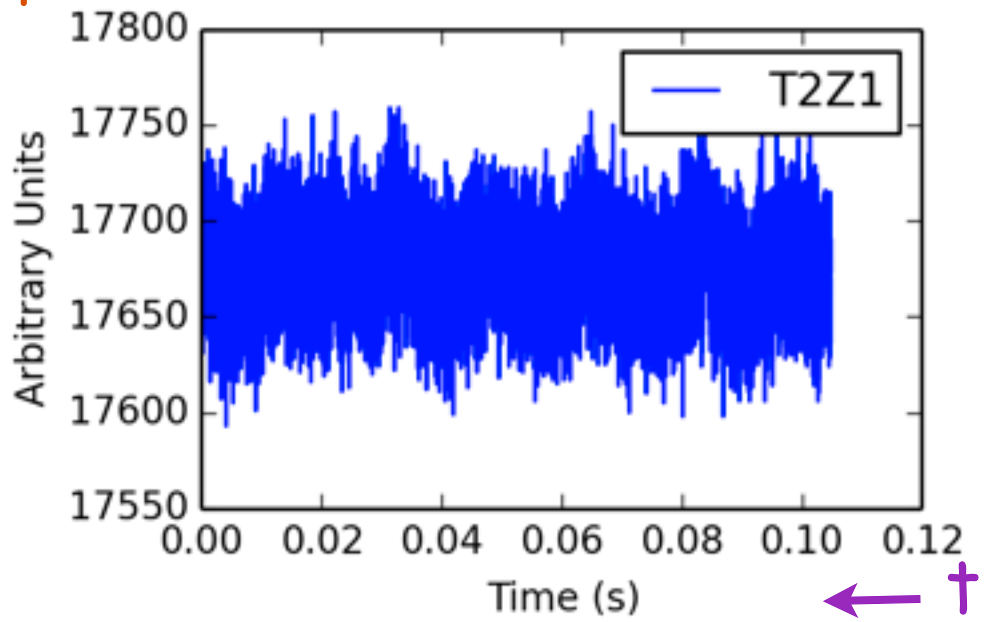
- 5 - 7 sigma (trigger threshold) range above noise during data taking

- Resolution of the filter reflects how small of a signal we can pick out from background

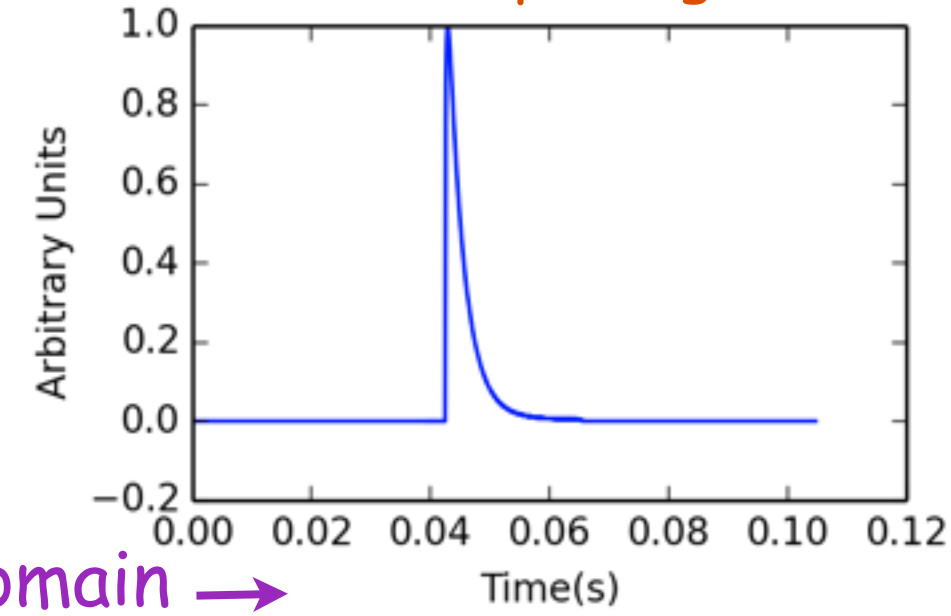
- Better filter ➜ smaller resolution ➜ lower threshold ➜ lower mass WIMP sensitivity

What Would the Background and Signal Look Like?

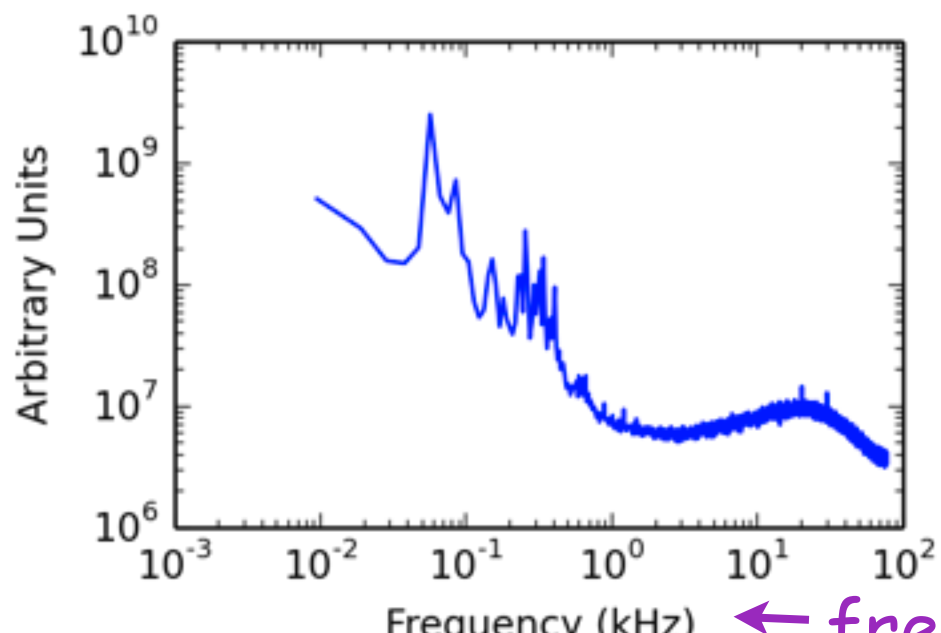
Example Noise of Detector T2Z1 in Soudan

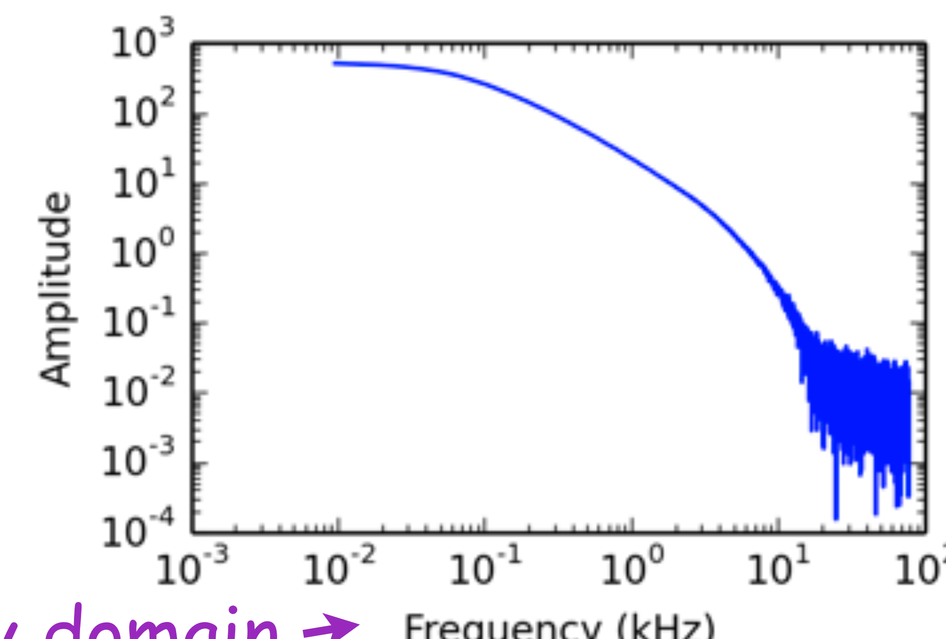


Example Signal



← time domain →





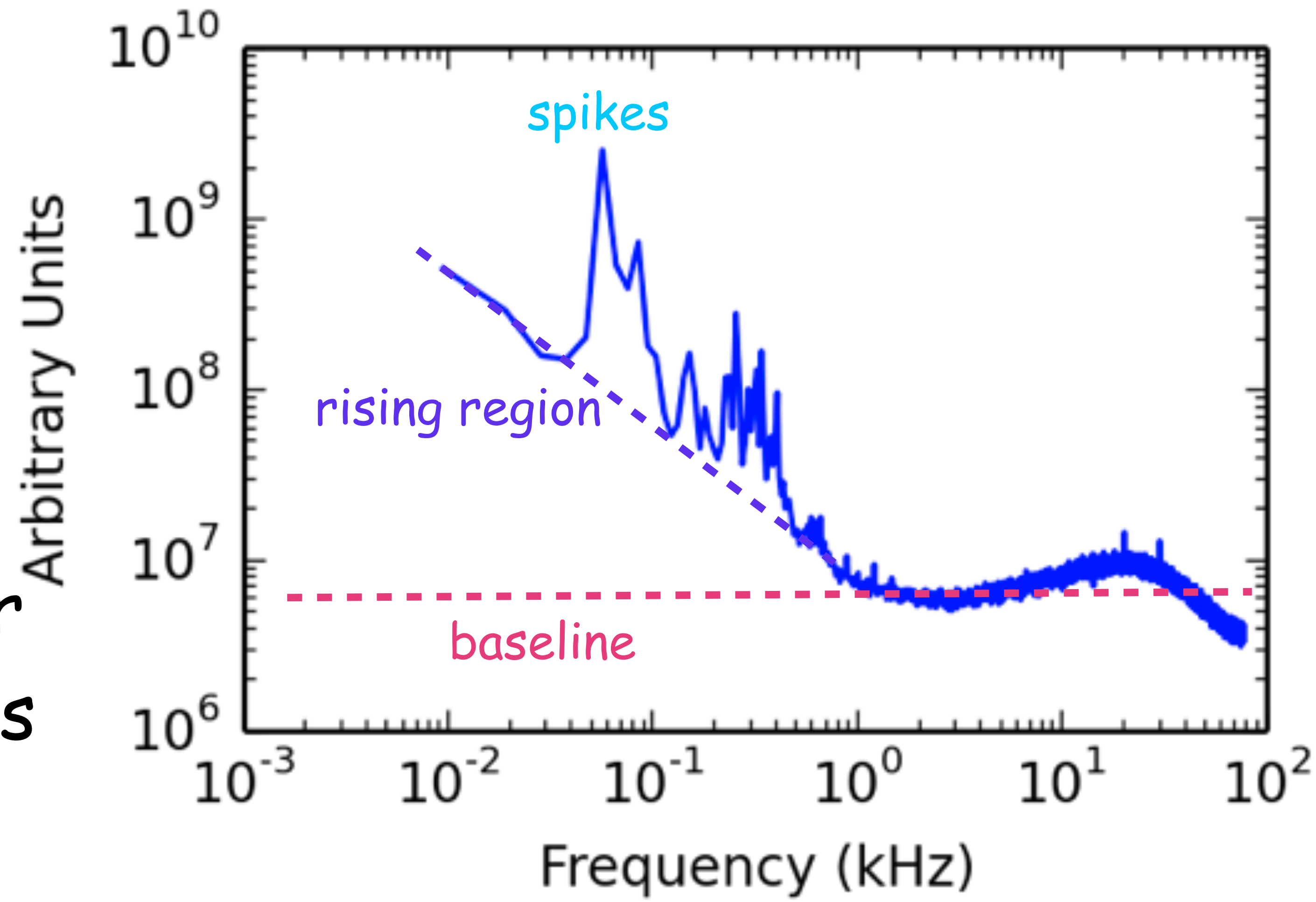
← frequency domain →

Our motivation:

Distinguish signal from noise in time or frequency domain

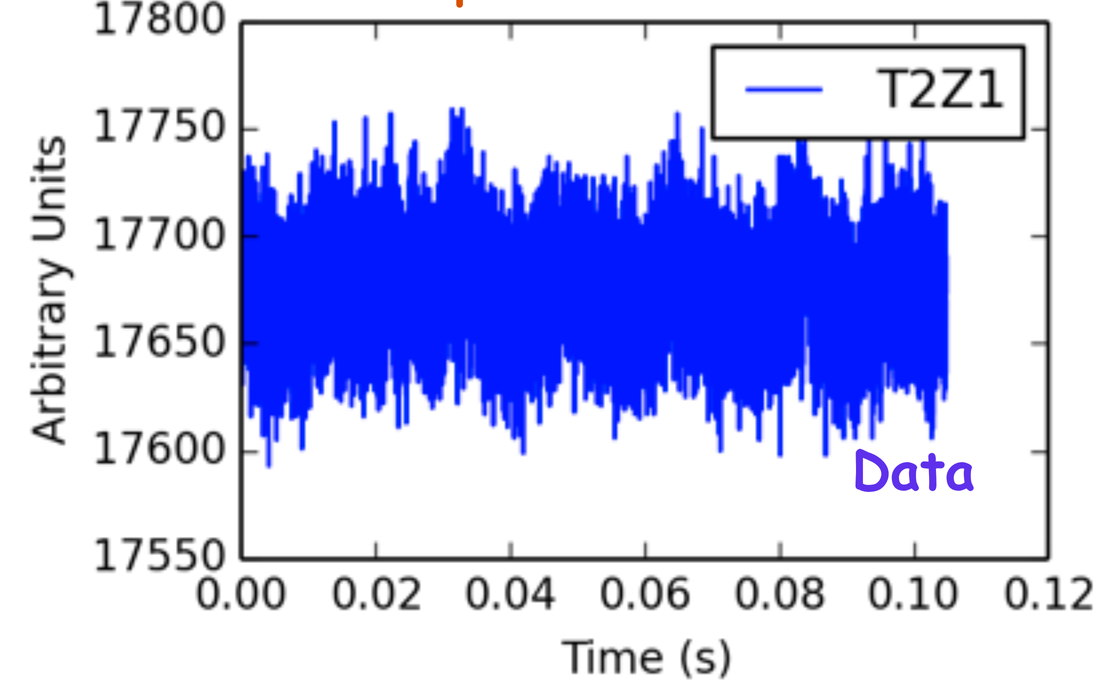
What causes the structure in the noise?

- Baseline noise: the TES/SQUID electronics (Johnson Noise)
- Rising Region: low frequency detector vibrations
- Spikes: various sources (cryogenics vibrations, detector electronics, or other electronics noise from amplification, triggering)

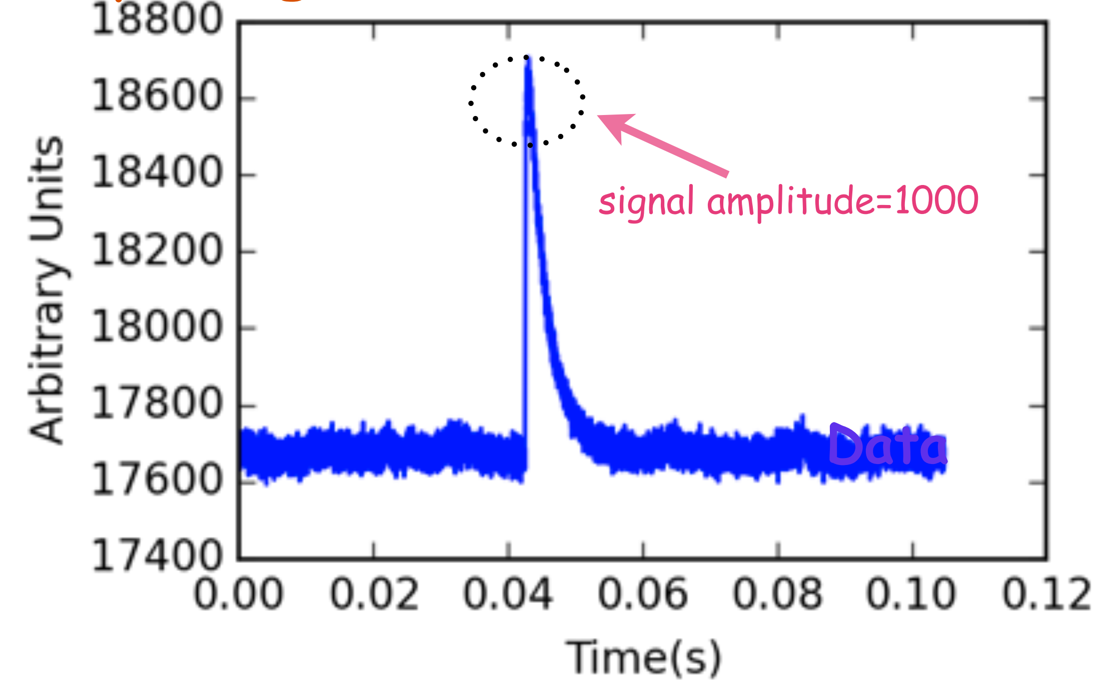


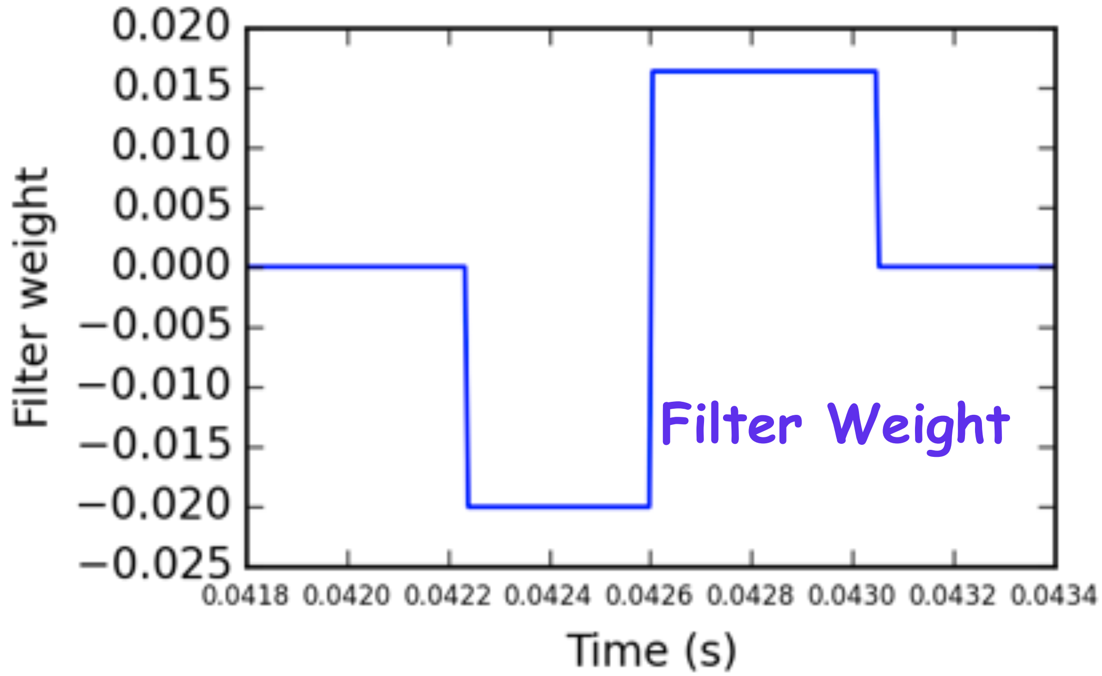
Using a Finite Impulse Filter (FIT) (using a box car shape)

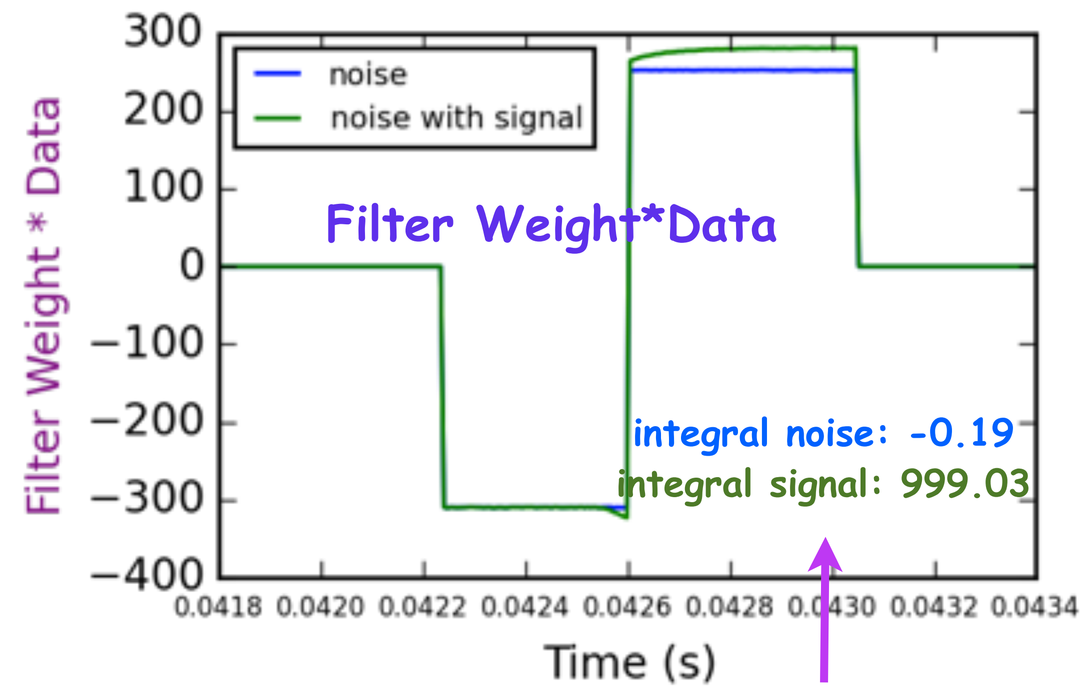
Example Noise Event



Example signal event with noise included





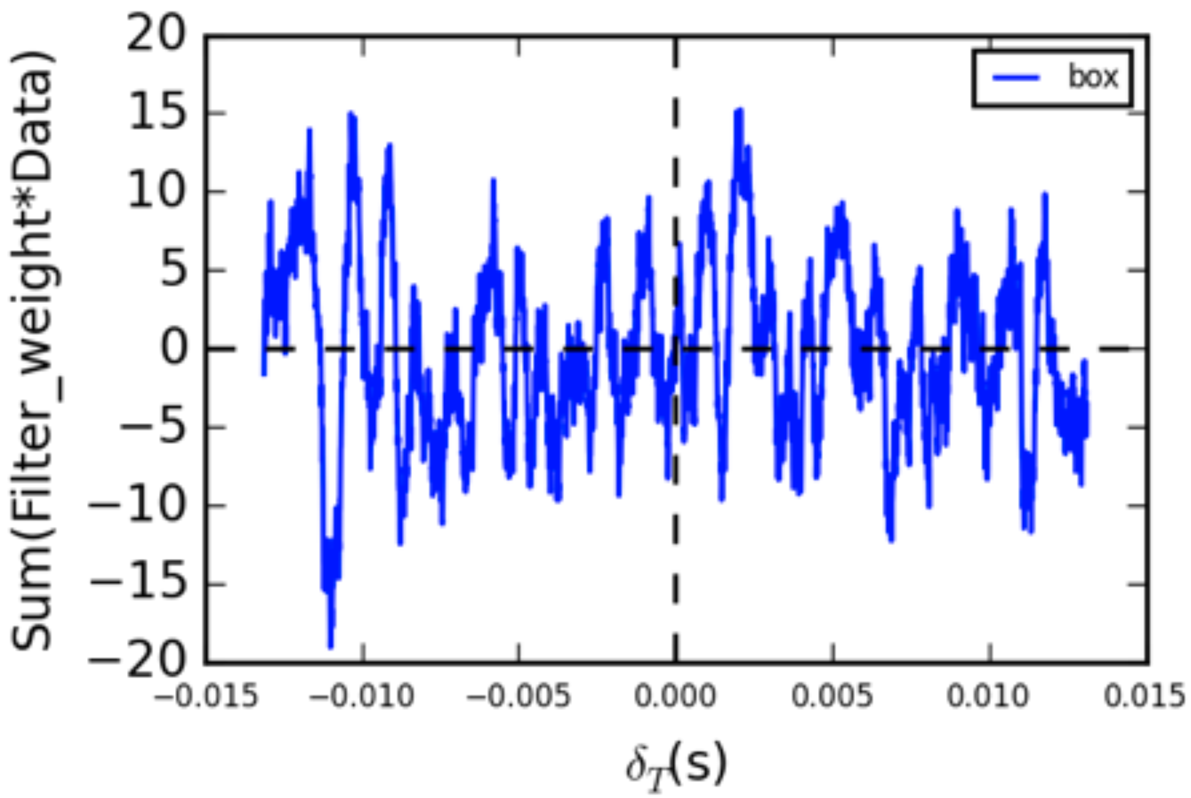


Sum (Filter_weight * Data) = Estimated signal amplitude

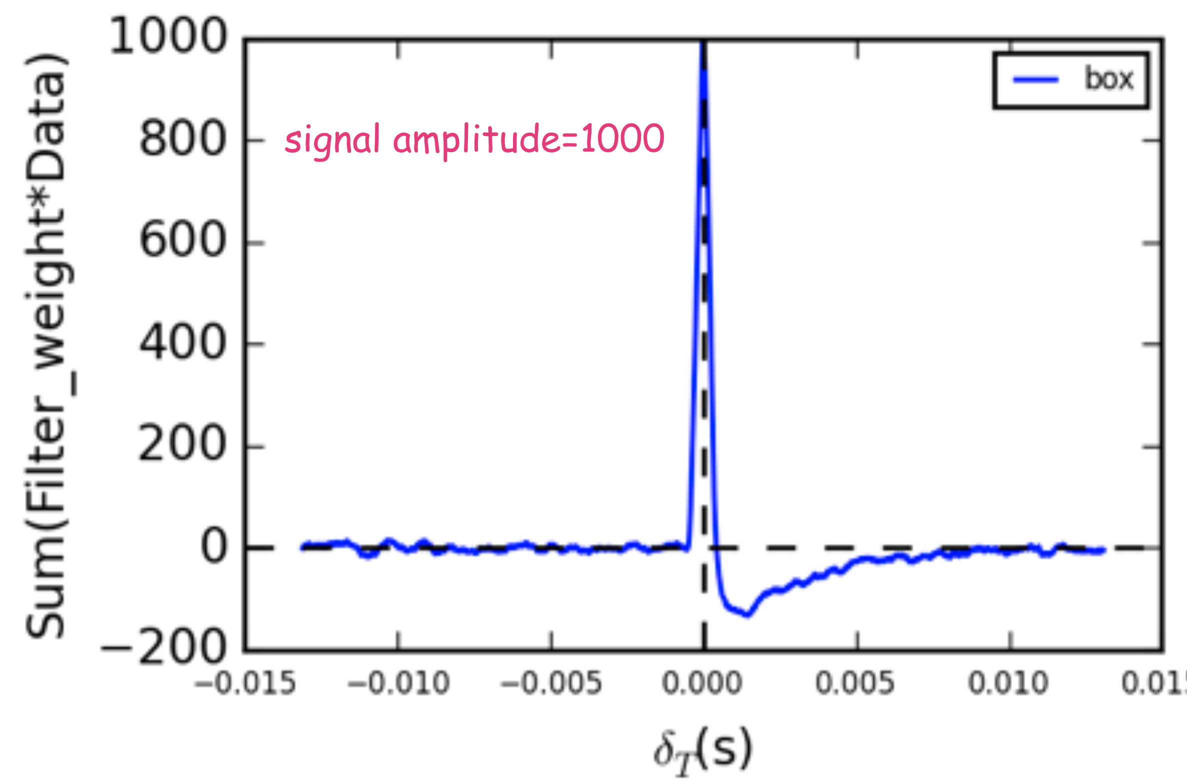
Filter Resolution

(when we move the filter along the data in time)

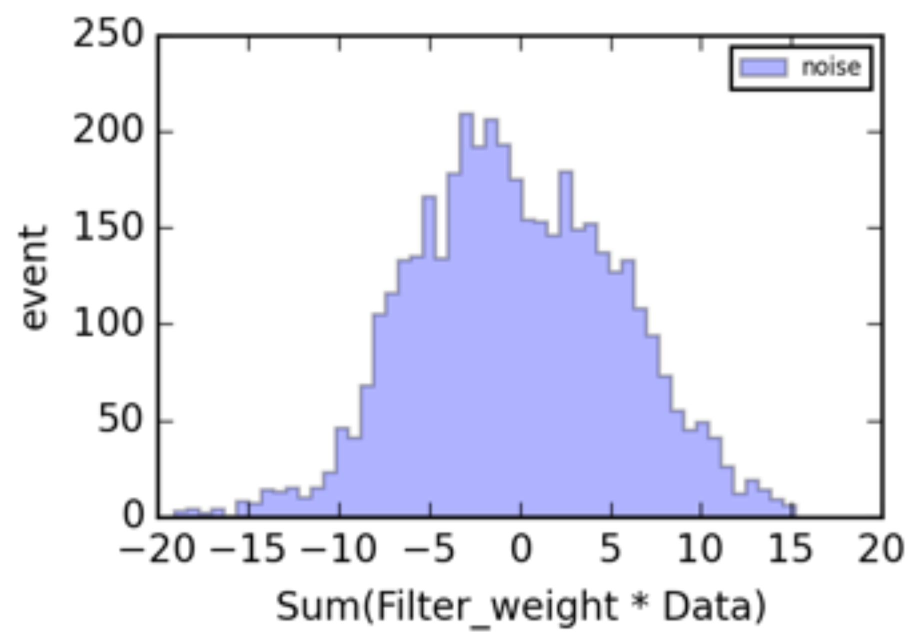
Example Noise-Only Event



Example Event with Signal

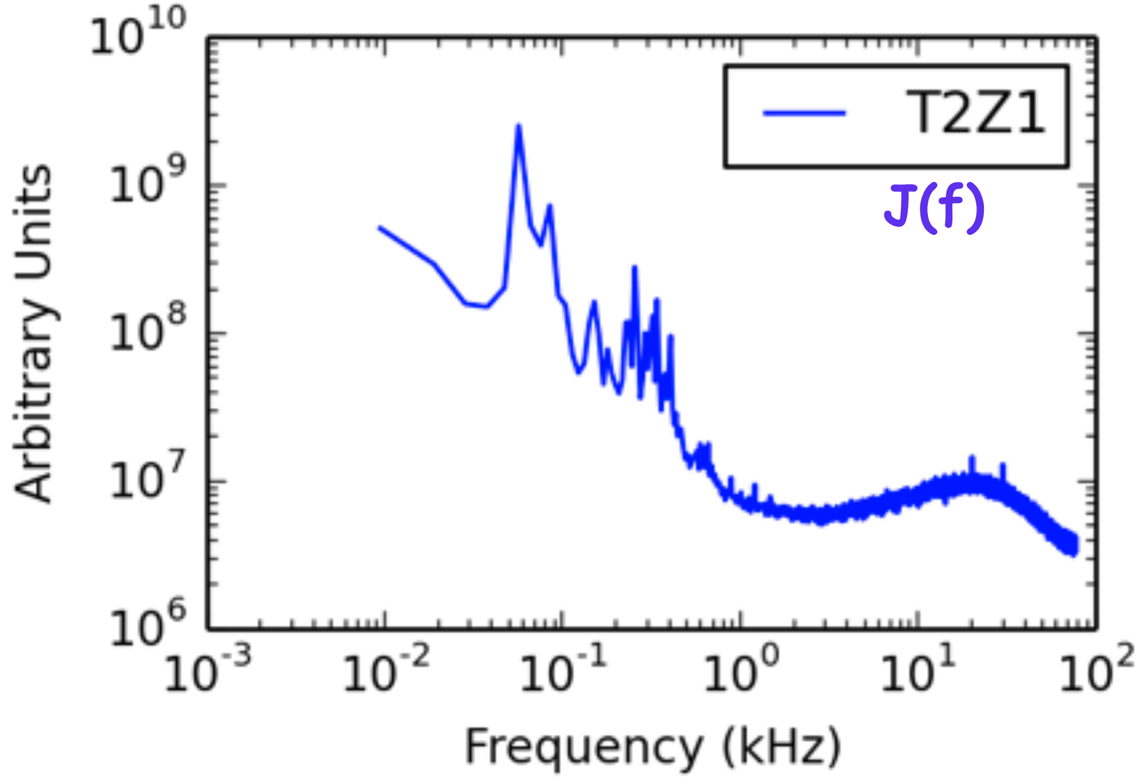


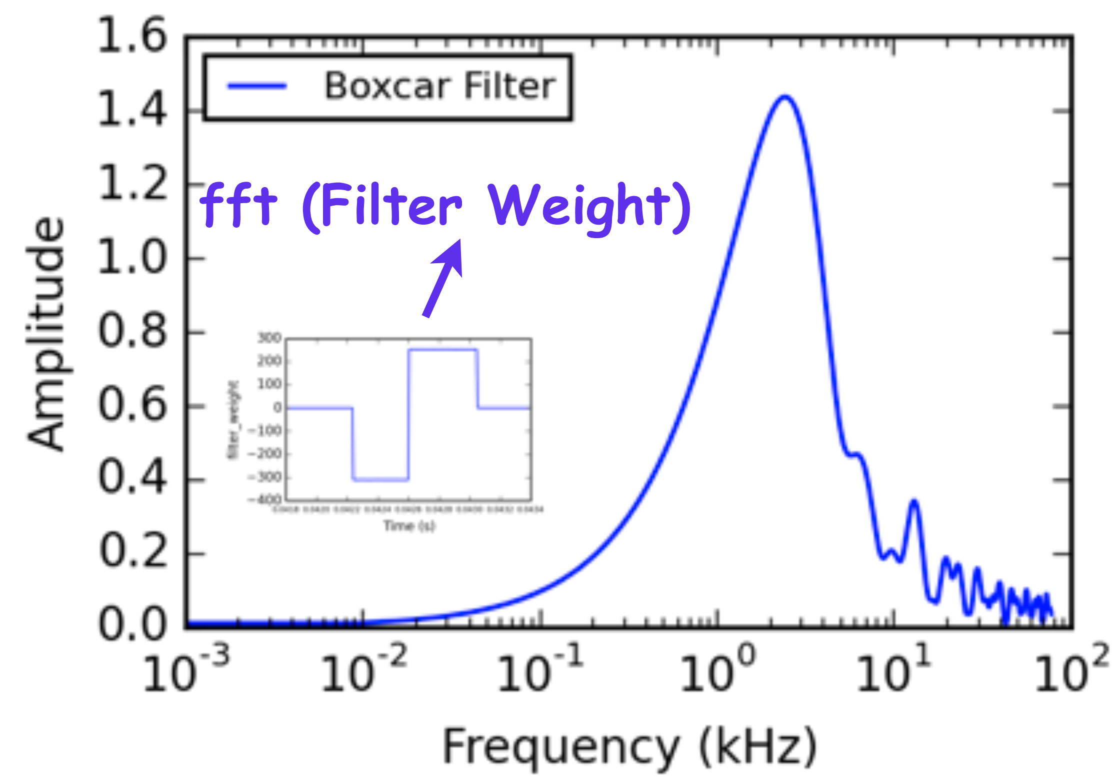
Histogram of top left plot →



Resolution: σ = 5.65

Calculate the Expected Resolution Analytically





- Straightforward to calculate the resolution as a function of frequency
- Gaussian random noise on each frequency
  → the resolution on each frequency = $\sqrt{J}$
- Scale the resolution for each frequency by the filter weight in frequency domain
- Add the uncertainty in quadrature due to the uncertainty propagation

$$\sigma = \frac{\sqrt{\sum_f fft(filter\_weight)^2 * J}}{\sum_t filter\_weight * signal}$$

Filter Design Considerations

Consider 3 filter candidates:

1) box-car filters
2) bandpass filters
3) optimal filters

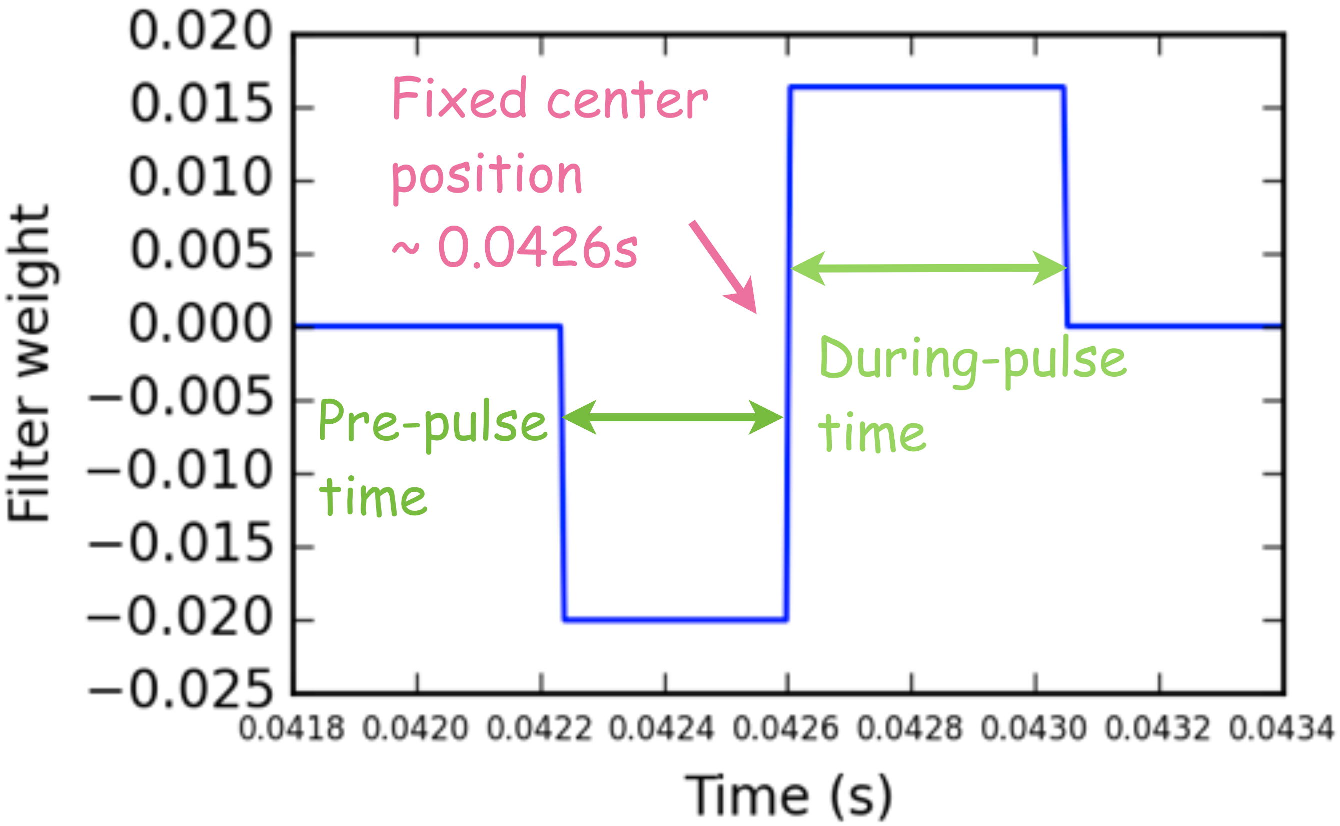
1) Resolution for each filter candidate

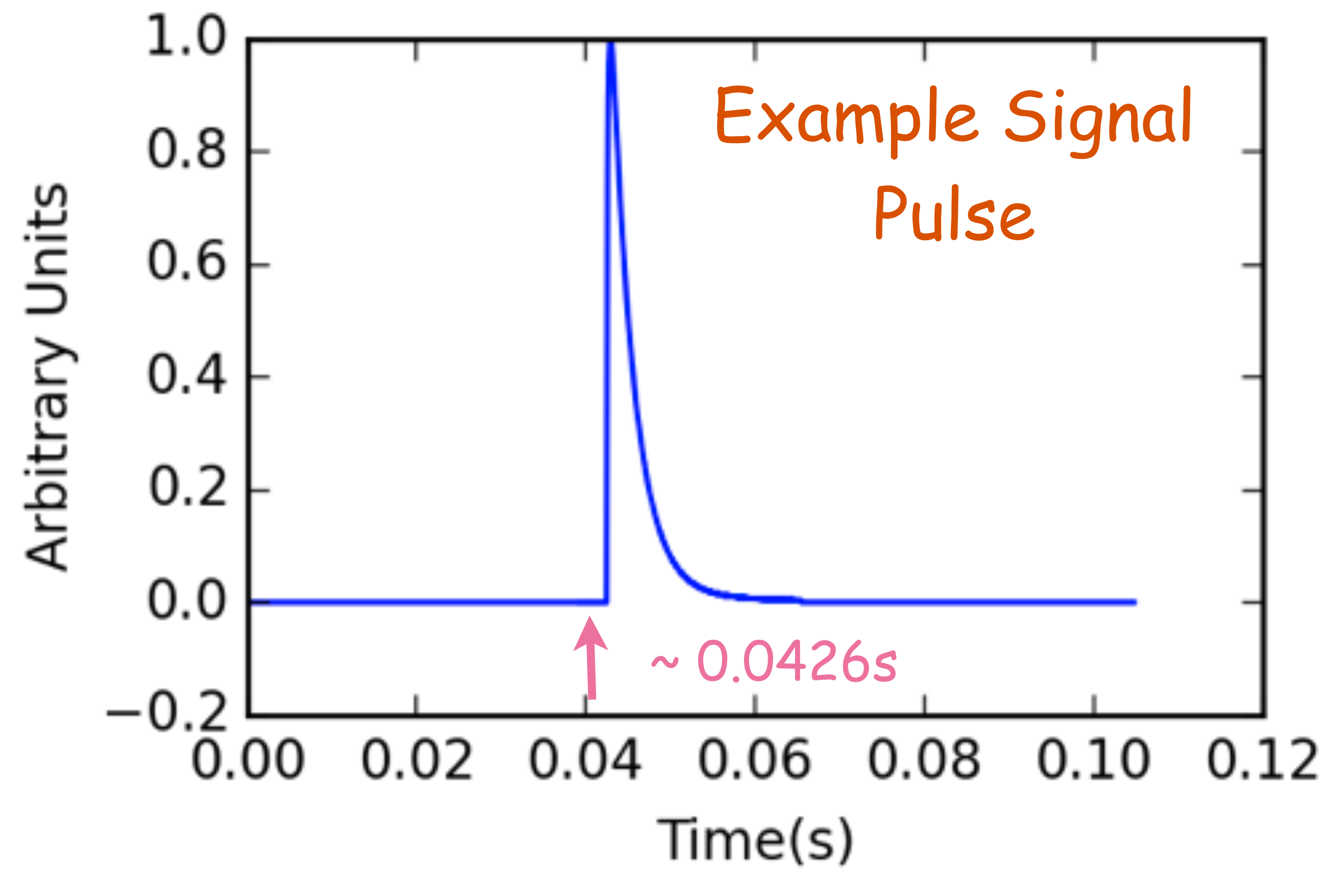
(Start by optimizing and determining the resolution for each assuming the Soudan background noise and signal shapes.)

2) Robustness to noise variation for each

(We have 11 detectors and 3 filter options. Run each detector through the different filter options and compare.)

Box-car Filter Parameters

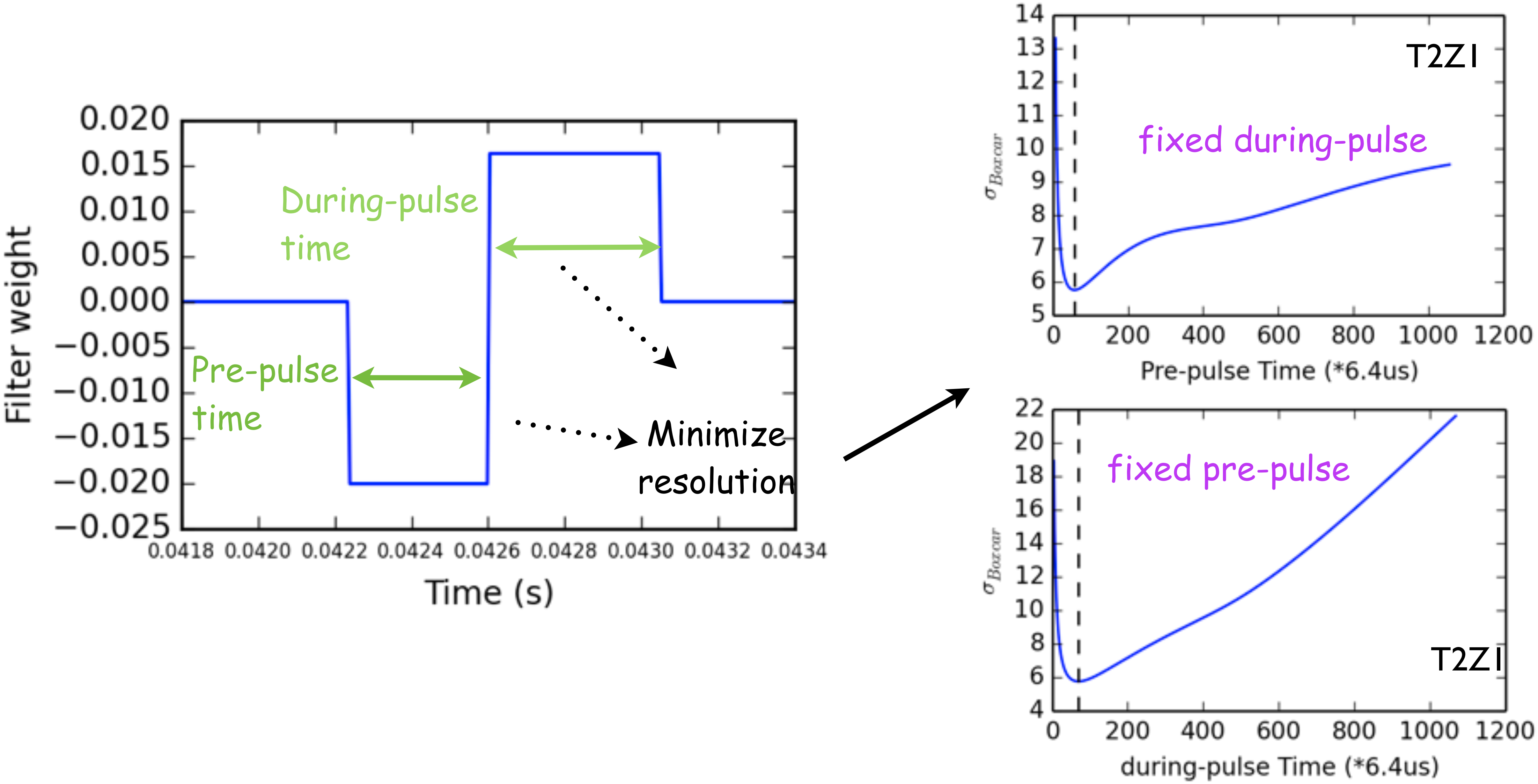




- Box-car filter is defined by two parameters: pre-pulse time and during-pulse time
- Fixed the center position at ~0.0426s, and the area under the curve is zero by construction (Note that this filter is compared to the data as the data pulse moves by in time. We are looking for the peak. For our studies we fix it as being at the center)
- Needs to be optimized detector-by-detector

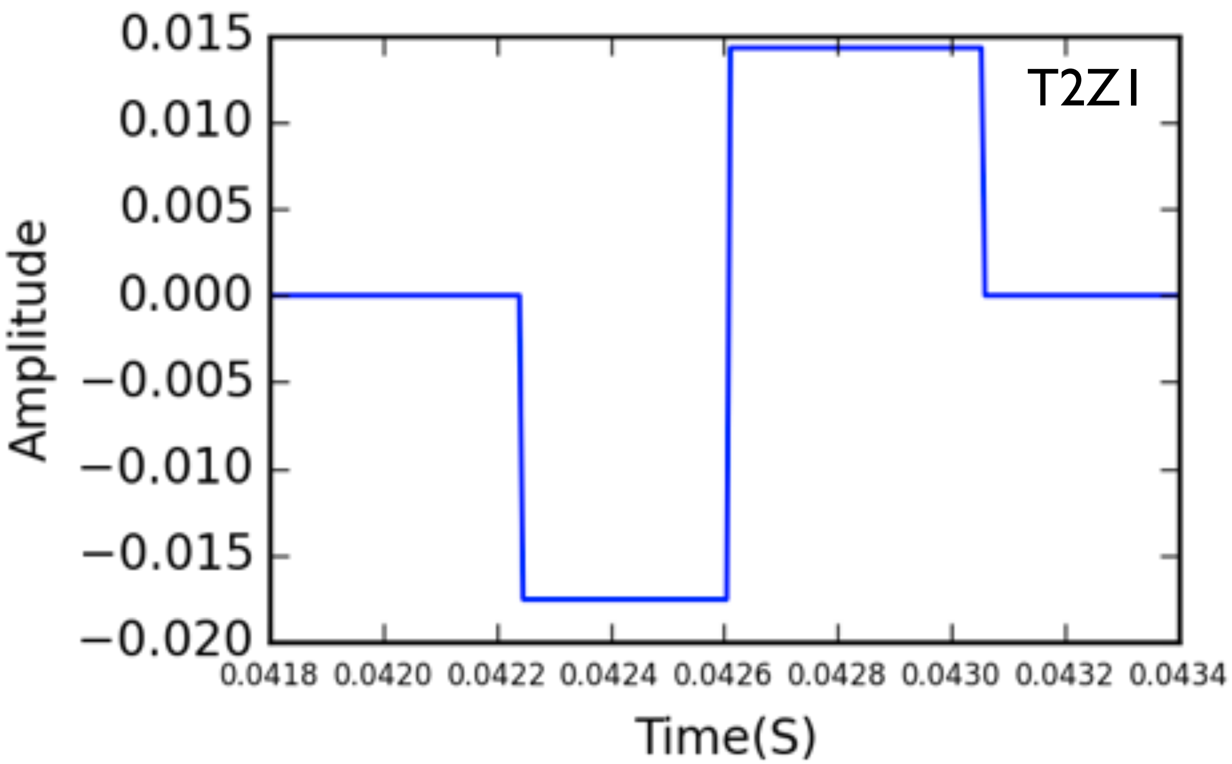
Box-car Filter Optimization

How does the resolution vary as a function of the two parameters?



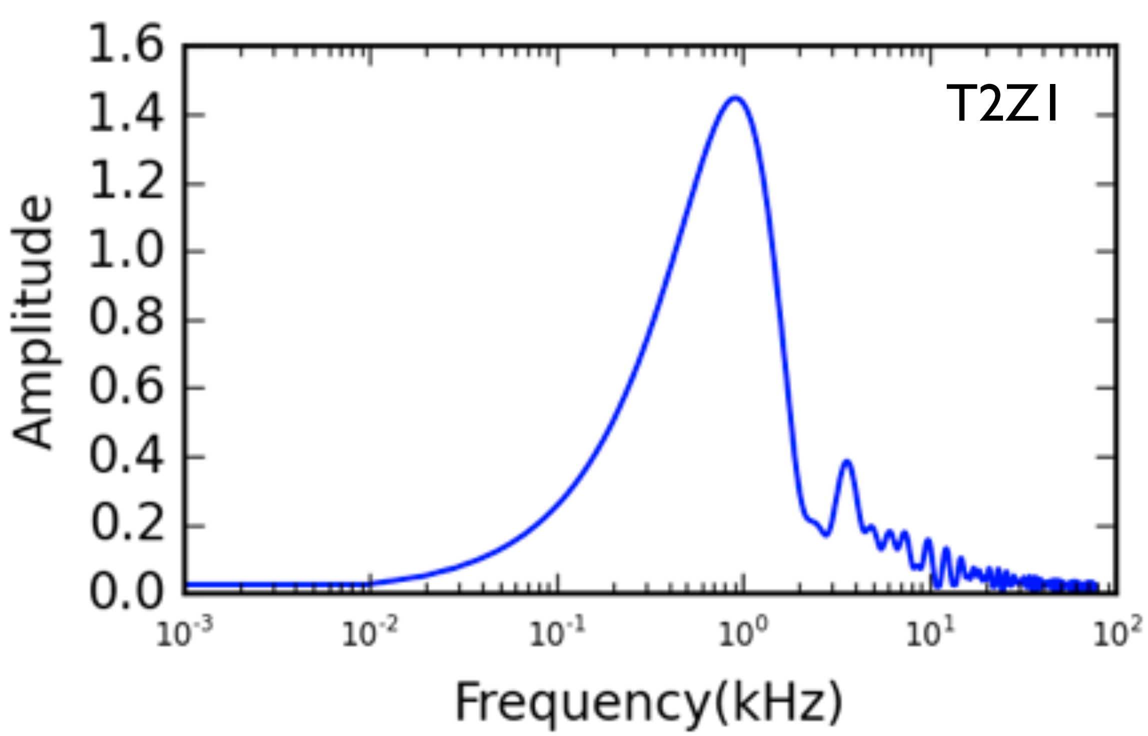
- Optimize the boxcar filter by changing pre-pulse time, during pulse time simultaneously

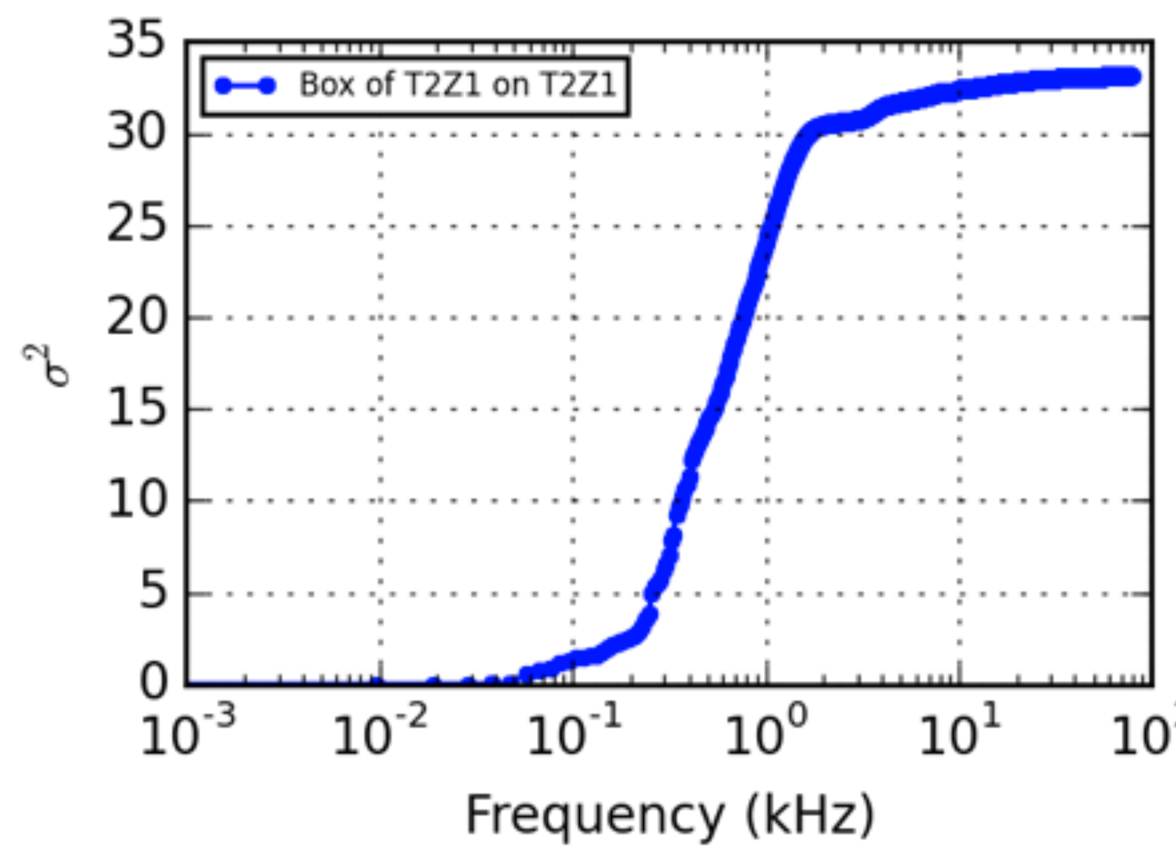
Optimized Box-car Filter



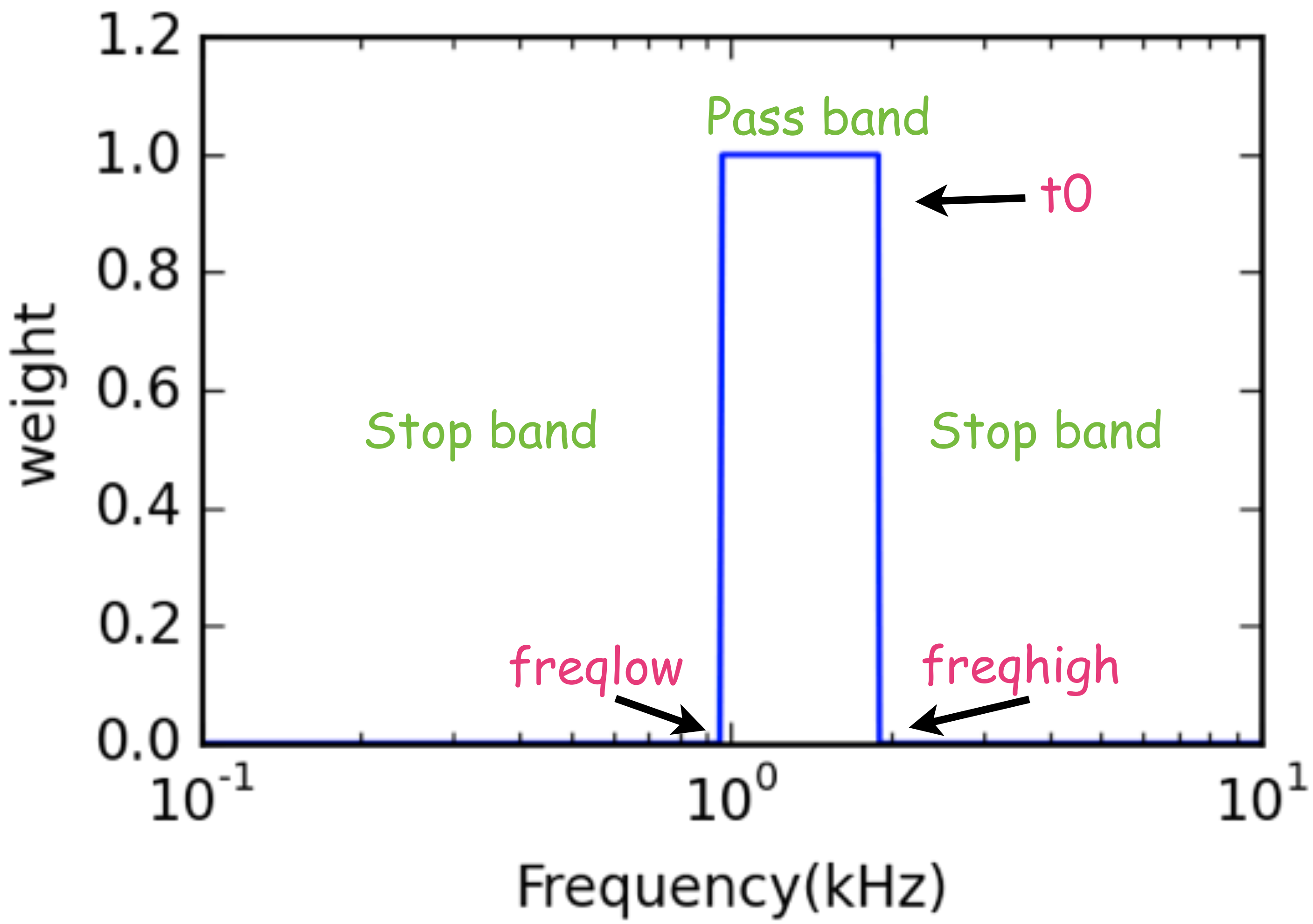
Resolution: $\sigma = \sqrt{(33.1)} = 5.75$

(We get basically the same answer as the previous method on page 13)





Option 2: Bandpass Filter



- Bandpass filter is defined by three parameters:

  1) freqlow → where the band starts

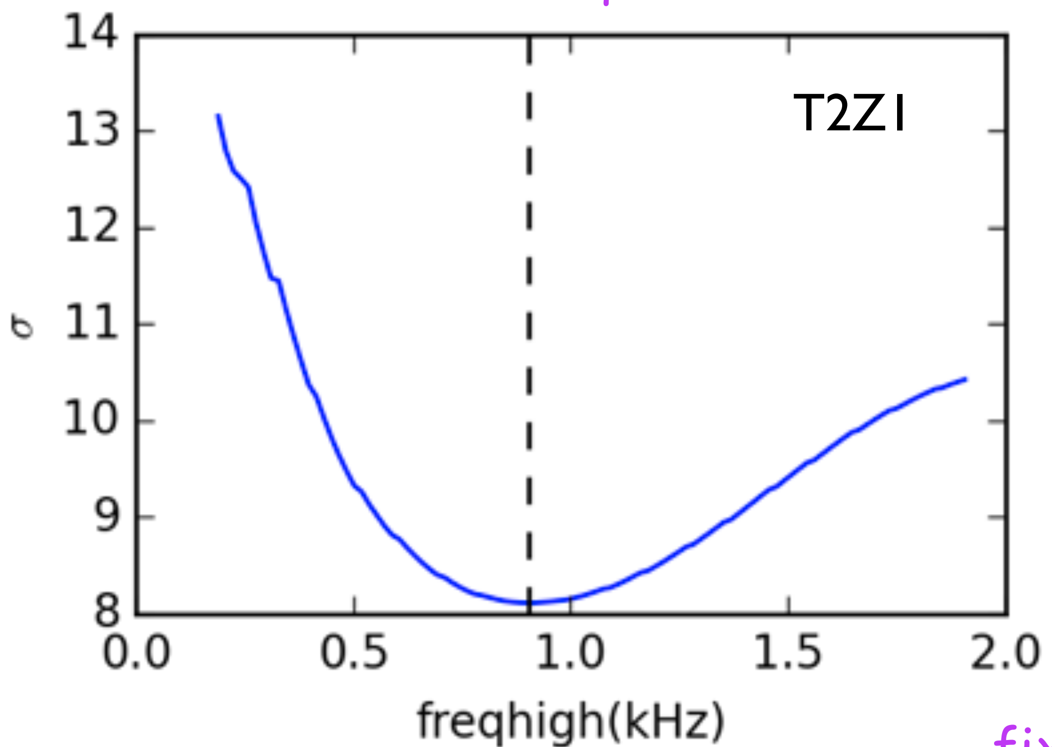
  2) freqhigh → where the band ends

  3) t0 → related to the phase of filter

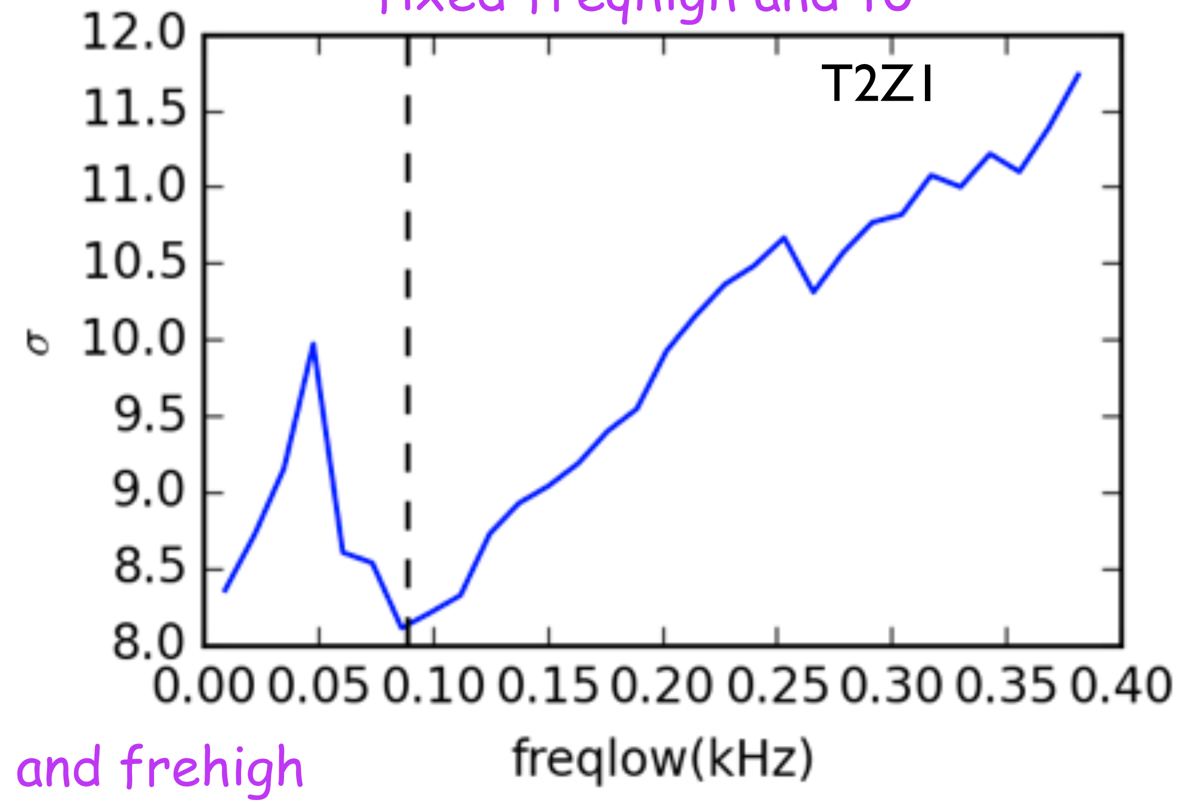
Bandpass Filter Optimization

How does the resolution vary as a function of the three parameters?

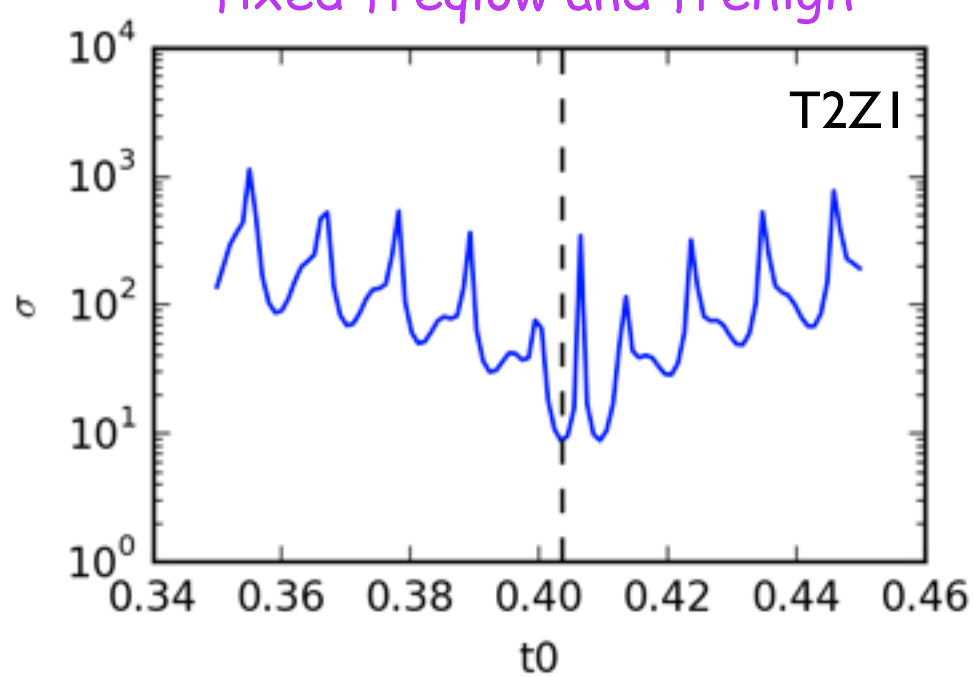
fixed freqlow and t0



fixed freqhigh and t0



fixed freqlow and frehigh



Option 3: Optimal Filter

- Optimized through calculation
- Signal traces $S(t)= aA(t) + n(t)$

  a - signal amplitude

  A(t) - known signal template

  n(t) - noise realization with noise PSD

Estimate a

Optimal technique for amplitude estimation:

➜ Calculate X^2 at frequency domain

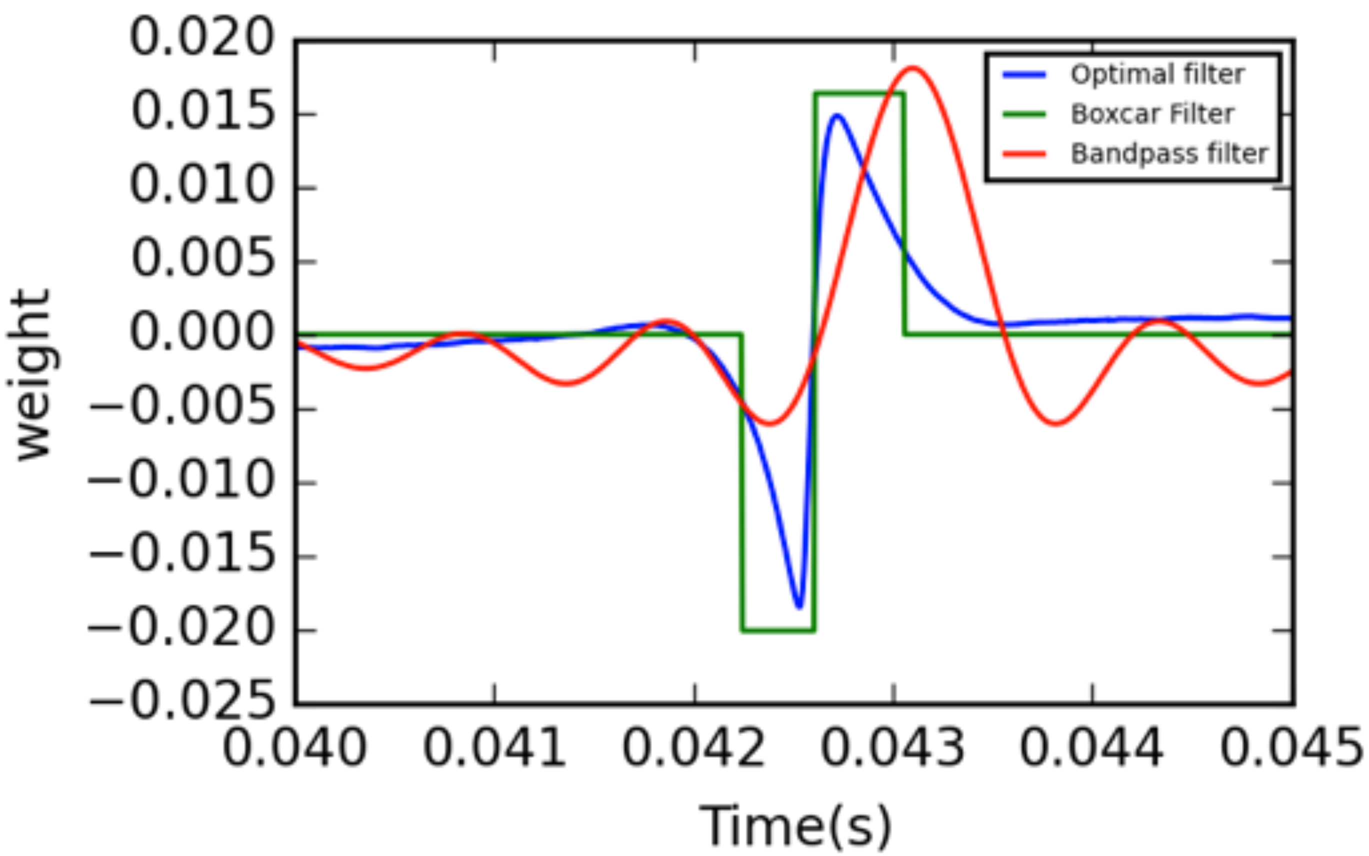
➜ Minimize the X^2

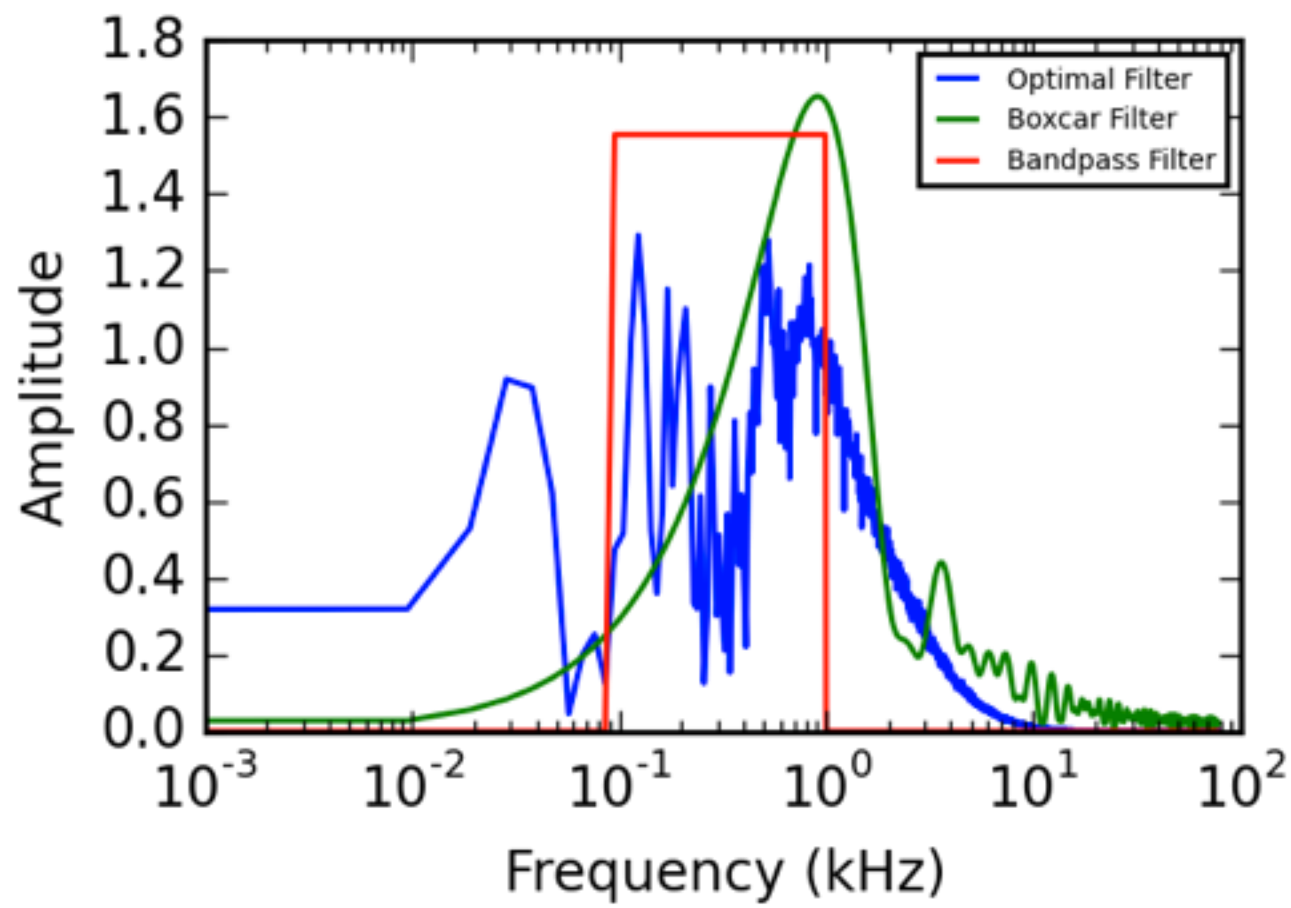
➜ Obtain optimal value for a

➜ Obtain optimal filter

Optimal Filter Study

Calculate optimal filter by using signal template and noise



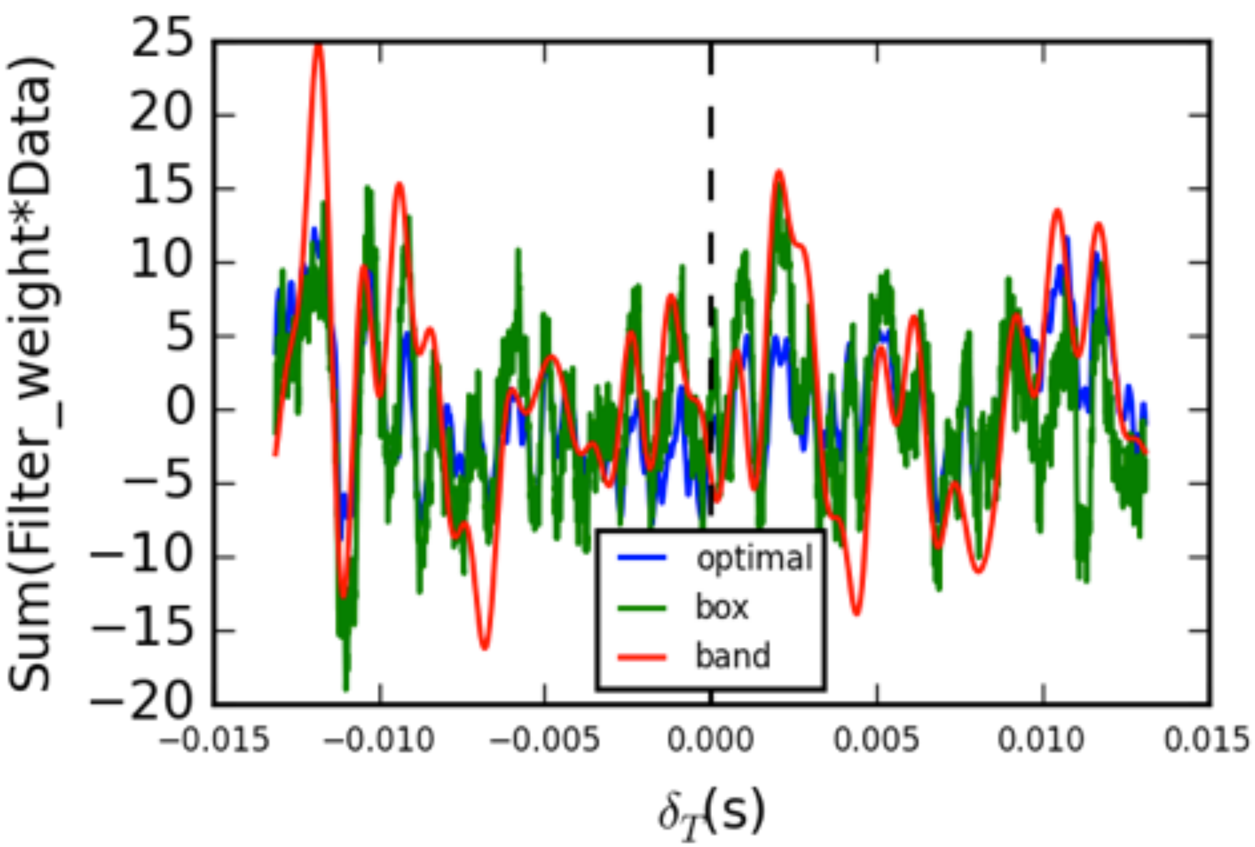


Comparison of the filter in time domain and the frequency domain. Similar as expected.

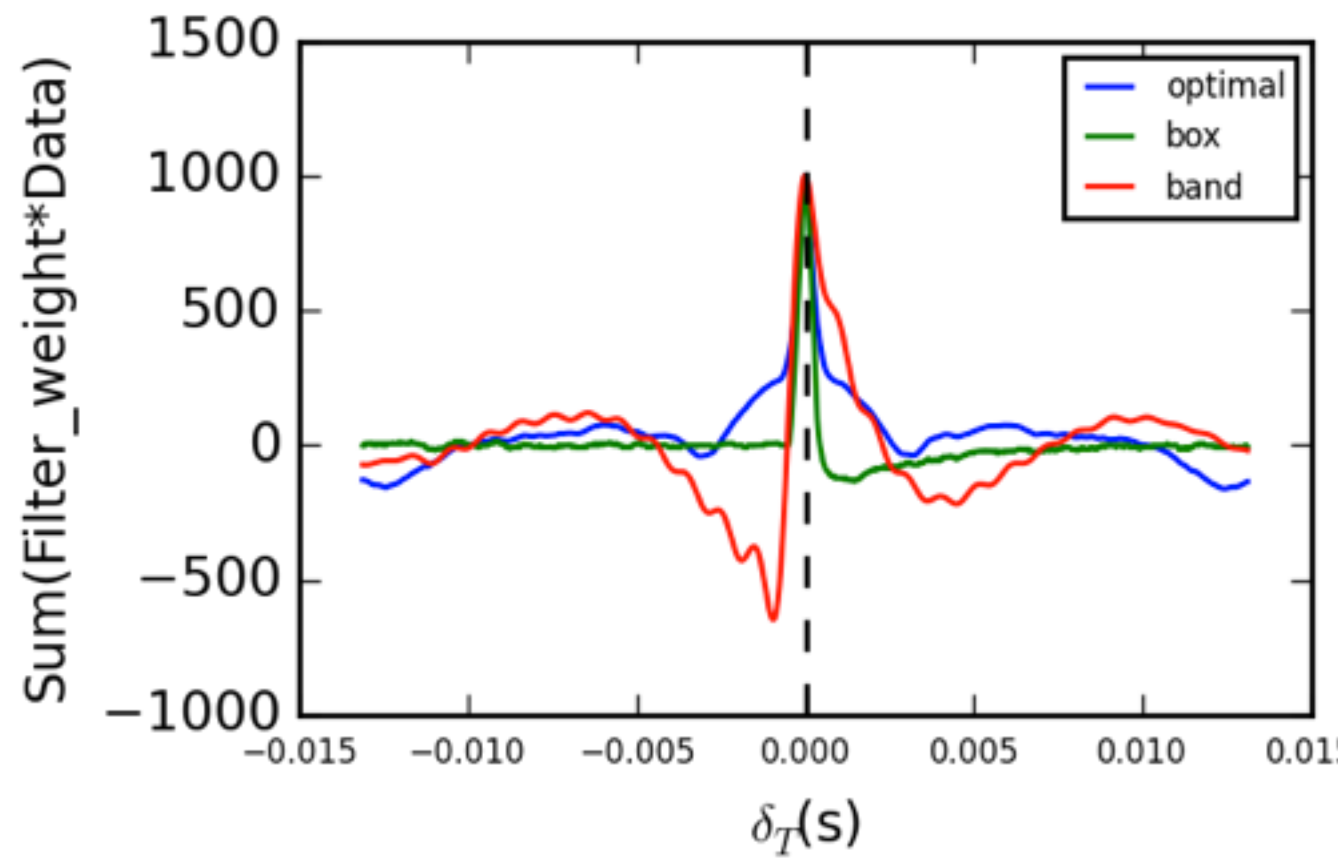
Filter Resolution

(when we move the filter along the data in time)

Example Event Noise-Only Event



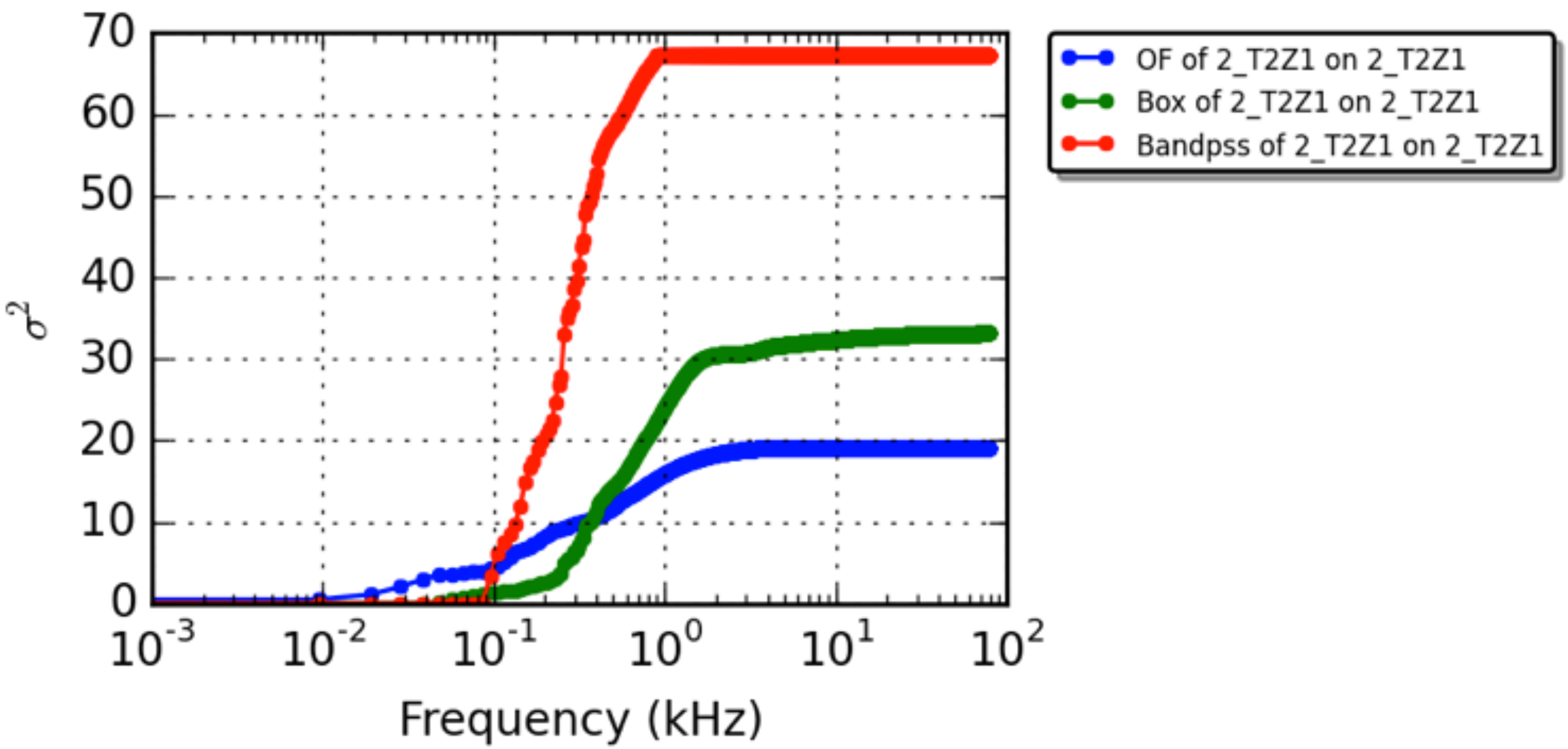
Example Event with Signal



- Filter rescaled so the amplitude of signal is the same as the input (e.g: all filters rescaled amplitude and integrated value of 1000 on right plot)

Comparison of the Boxcar, Bandpass and Optimal Filter Resolutions

square of resolution



- Resolution of three optimized filters for T2Z1:

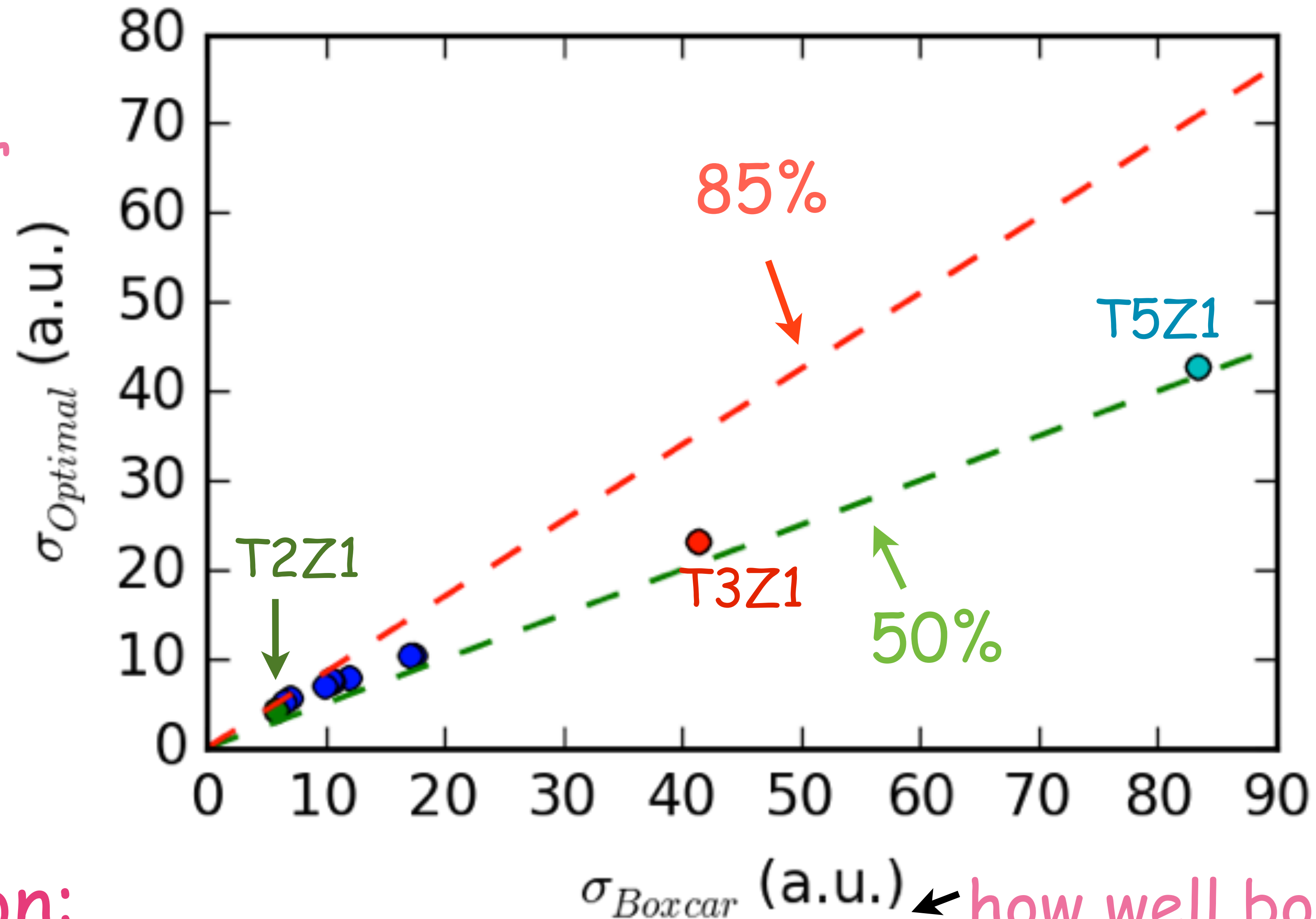
bandpass: 8.11

boxcar: 5.75

optimal: 4.38

Optimize each of the three filters for all 11 detectors from the real Soudan data

how well optimal filter works

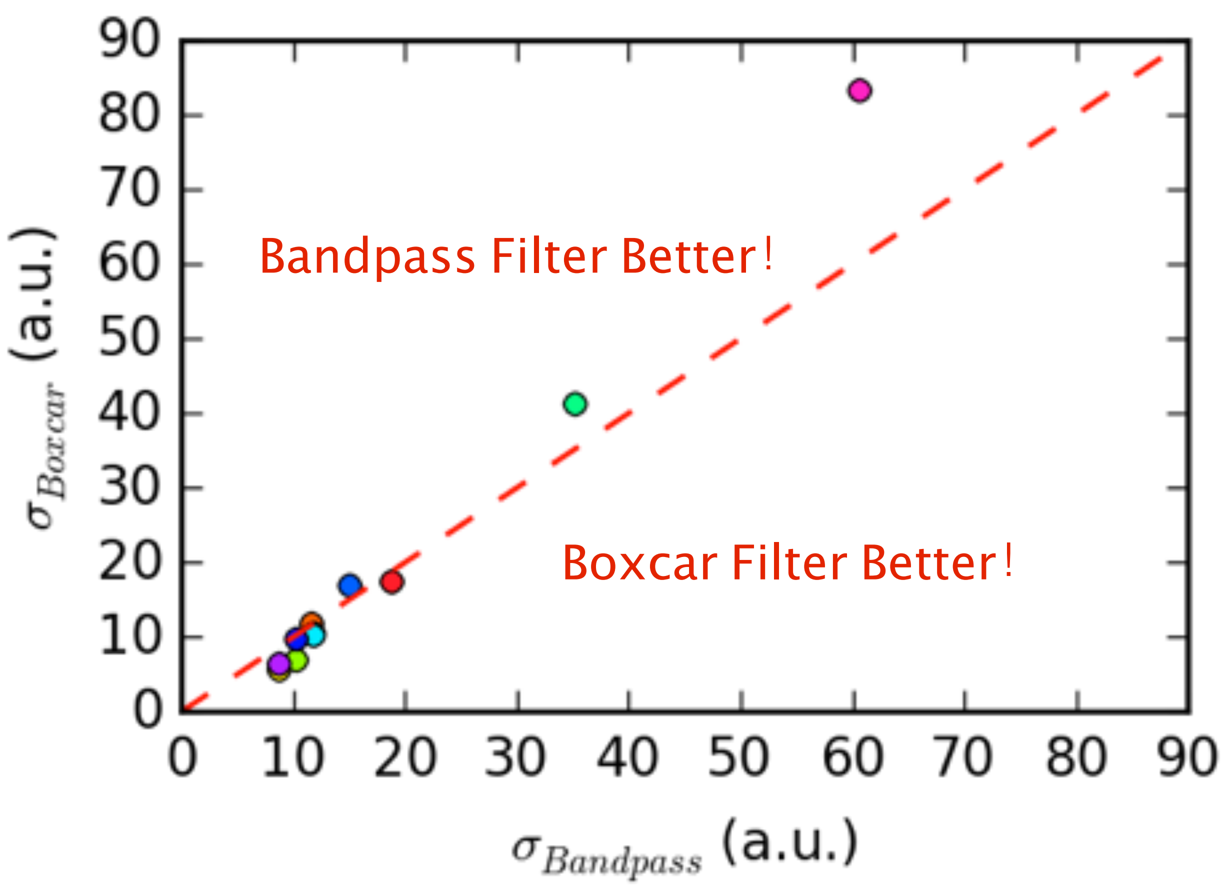


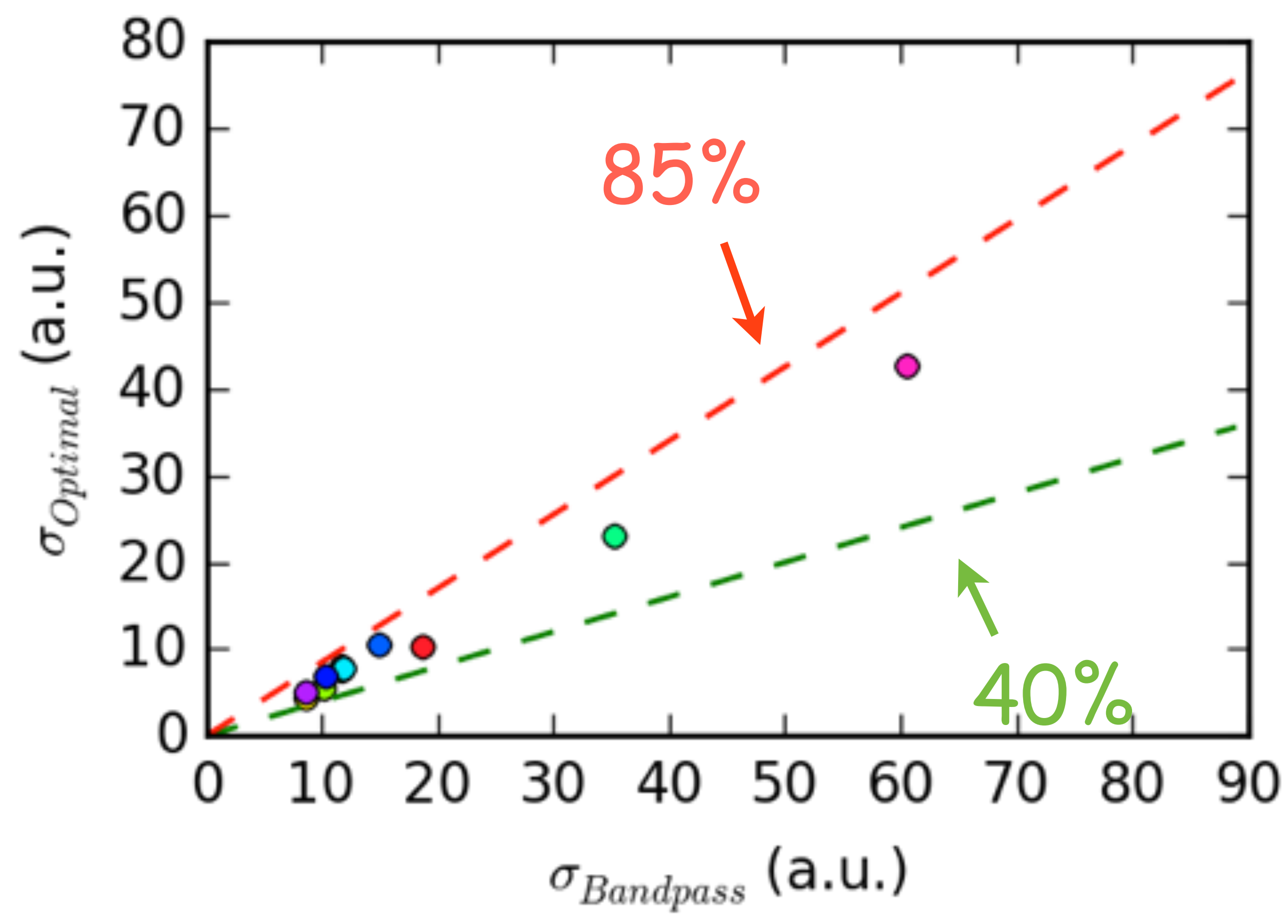
how well boxcar filter works

Conclusion:

- The optimal filter always has best resolution
- The resolution of optimal filter is between **50%** and **85%** of the boxcar

Compare all three filter types to each other





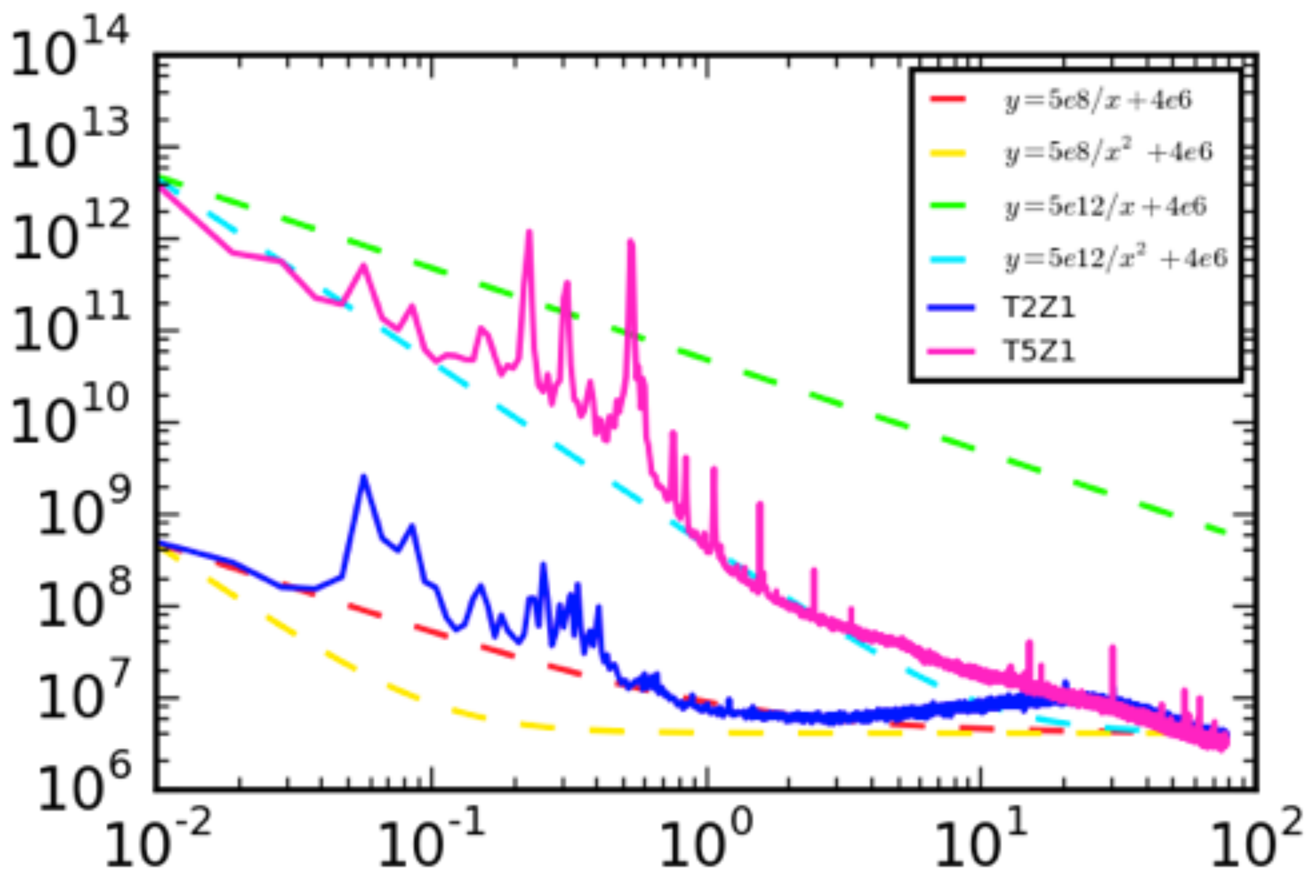
Conclusion:

- The bandpass filter is better than boxcar for large resolution
- The optimal filter always has best resolution
- The resolution of optimal filter is between **40%** and **85%** of the bandpass filter

How do the Various Components of Noise Contribute to the Resolution?

Two function option: $\frac{a}{f}+b$ and $\frac{a}{f^2}+b$

No spike in simplified noise!



$\frac{a}{f}+b$ is better for T2Z1

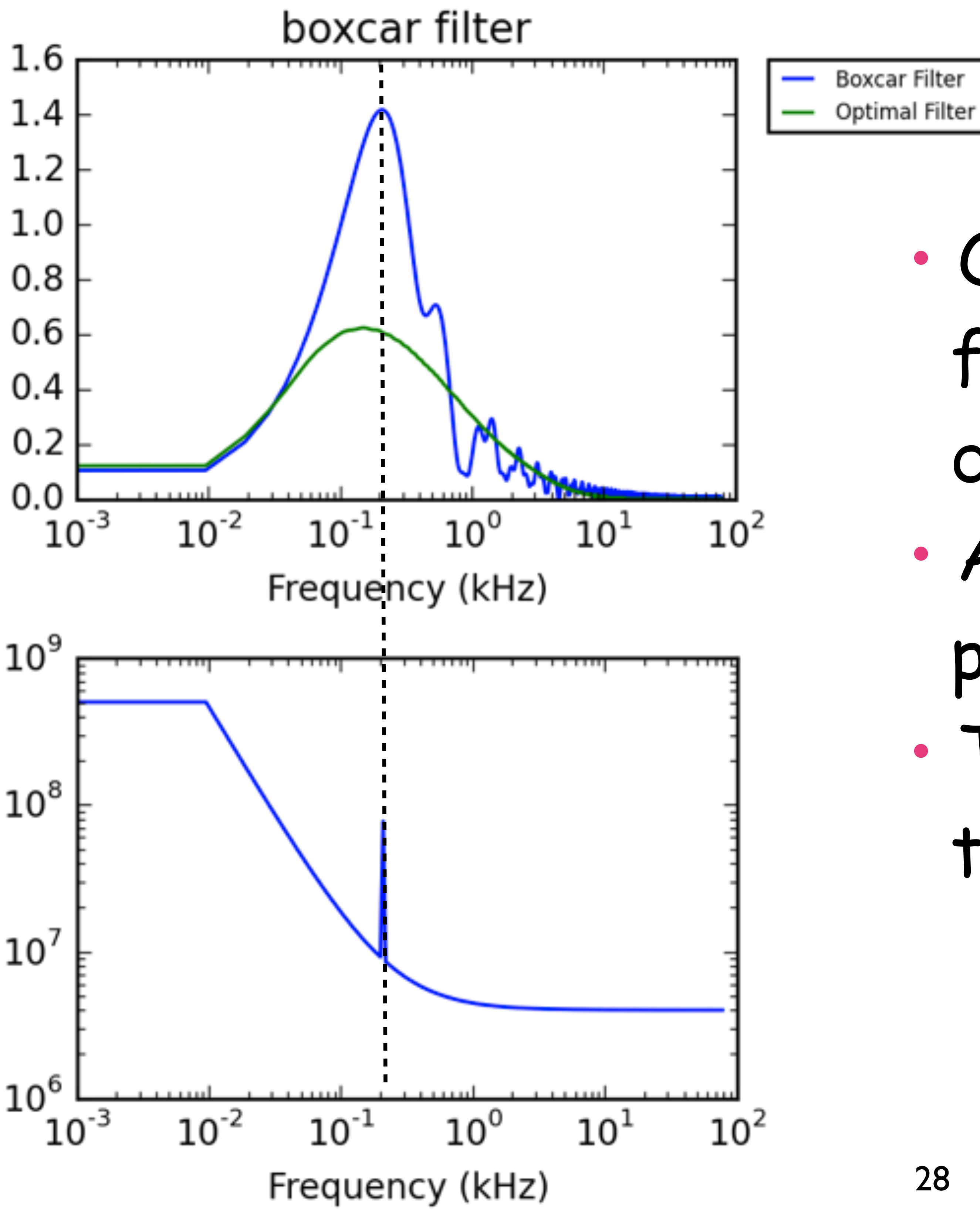
$\frac{a}{f^2}+b$ is better for T5Z1

Optimal/ Boxcar	Real Noise	$\frac{5\times10^8}{f}+4\times10^6$	$\frac{5\times10^8}{f^2}+4\times10^6$
T2Z1	4.4 / 5.8	3.3/ 3.9	1.6 / 1.8

Optimal/ Boxcar	Real Noise	$\frac{5\times10^{12}}{f}+4\times10^6$	$\frac{5\times10^{12}}{f^2}+4\times10^6$
T5Z1	42.8 / 83.3	287.3 / 348.9	36.6 / 37.6

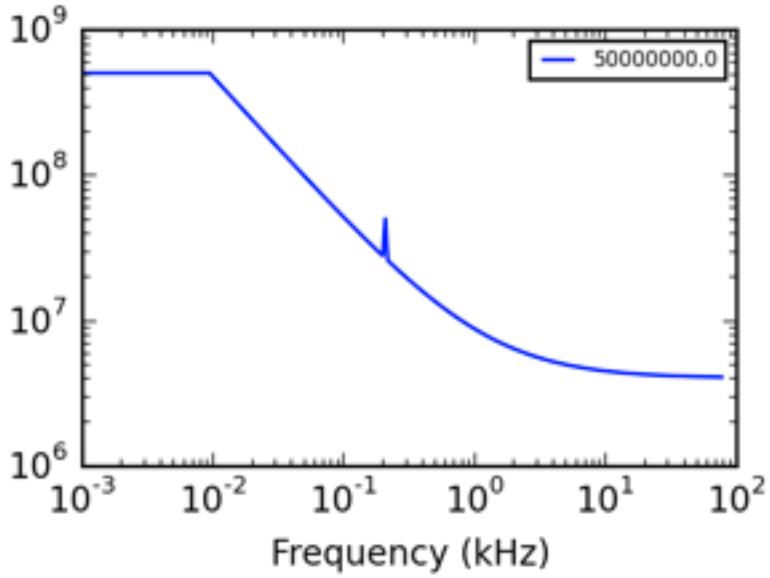
Extra spikes contribute about ~50% of the resolution!

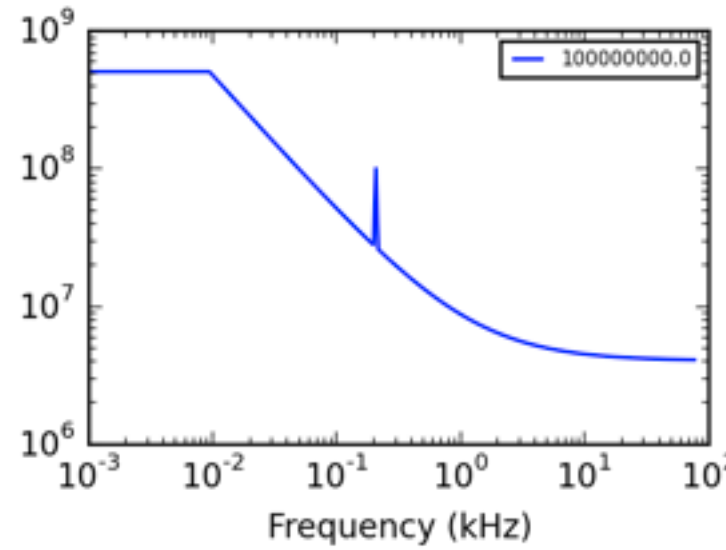
Study the contributions to the resolution by adding spikes to our simplified noise

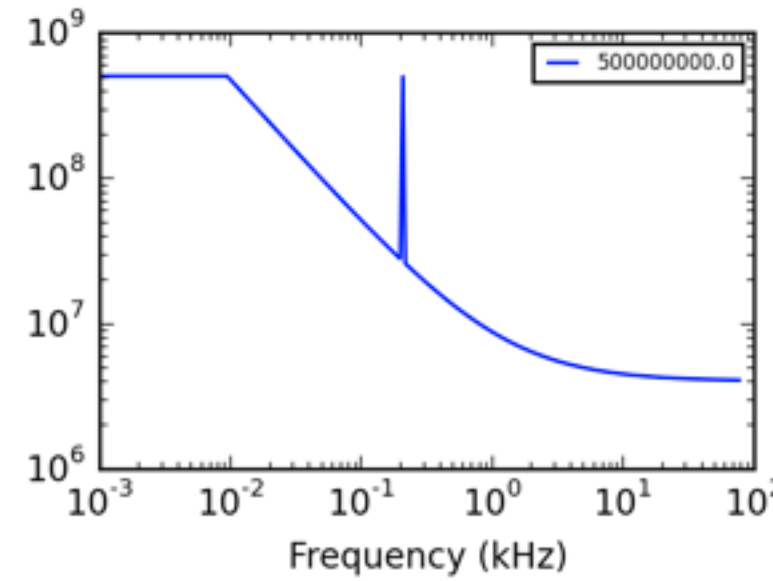


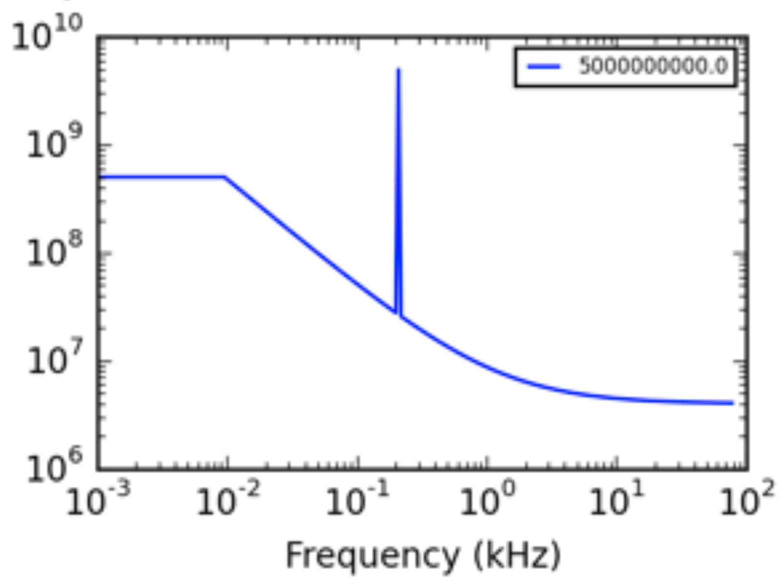
- Optimize a boxcar filter, find the peak in frequency domain
- Add a spike where the peak is in frequency space
- Then change the size of the peak

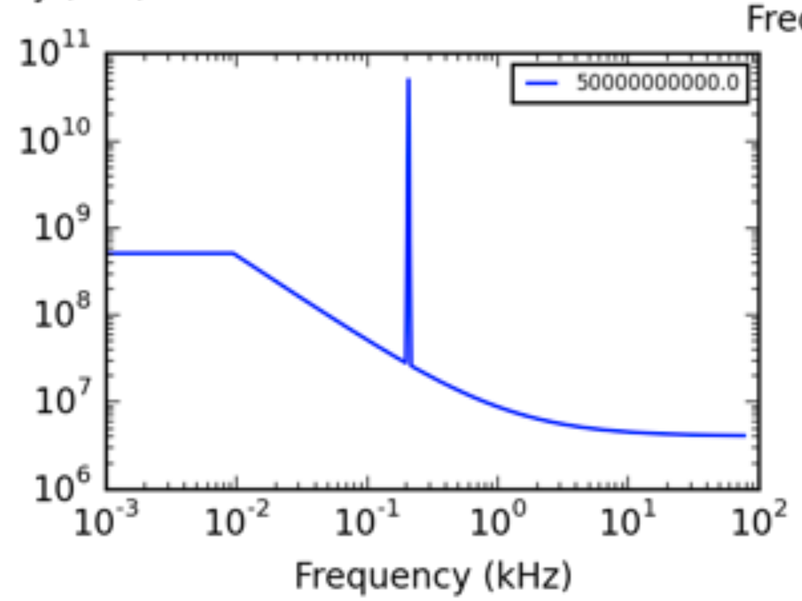
Choose Seven Different Spike Sizes For T2Z1 Simplified Noise

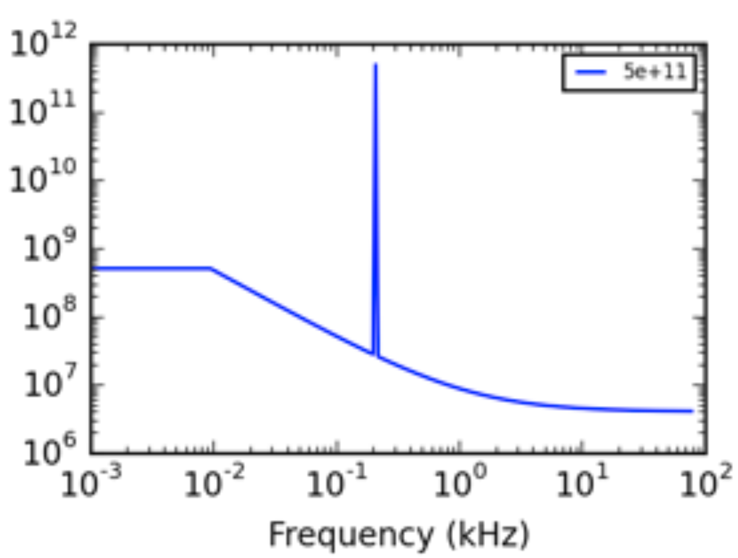


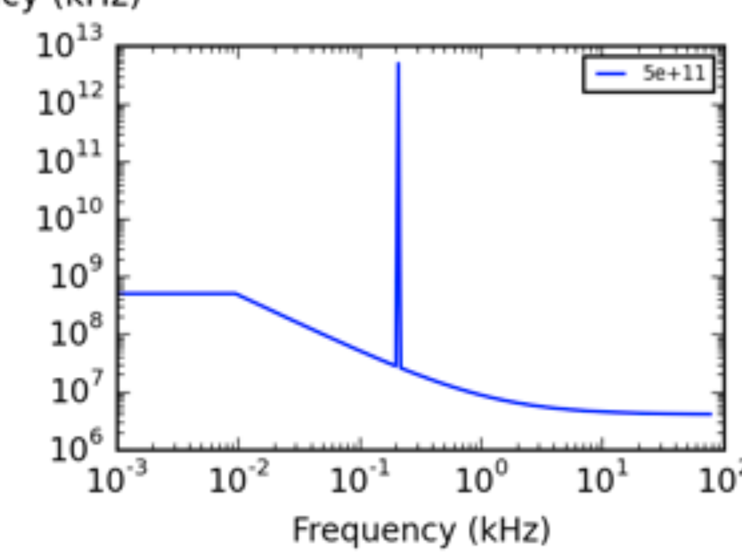




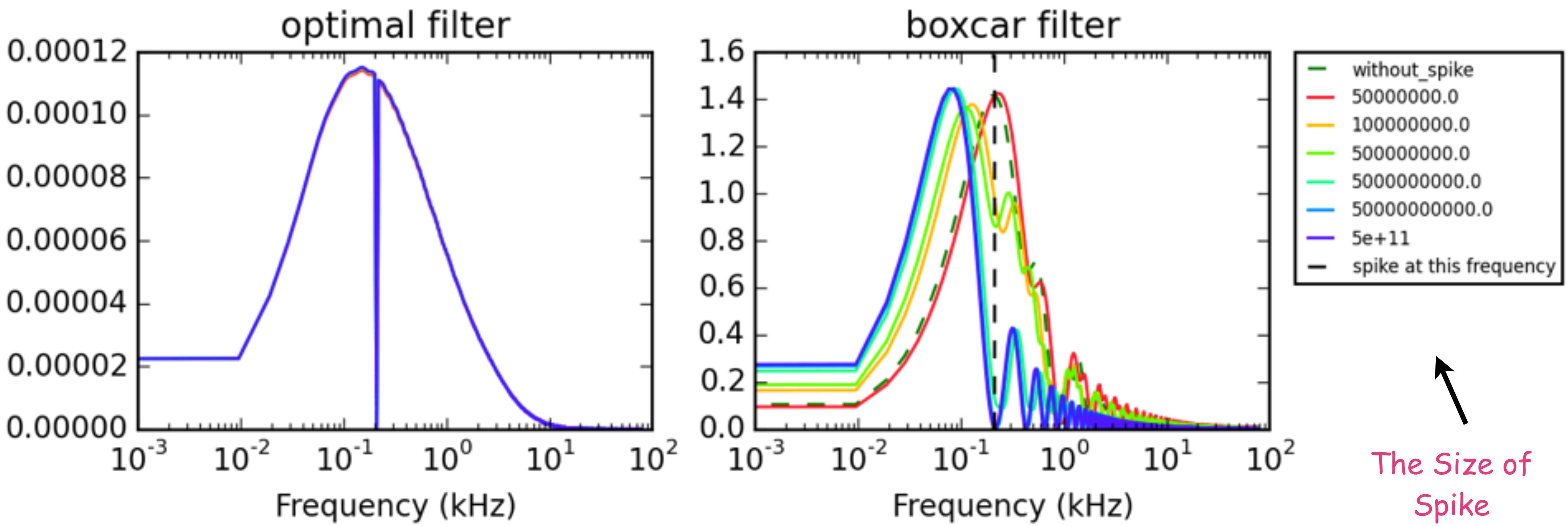






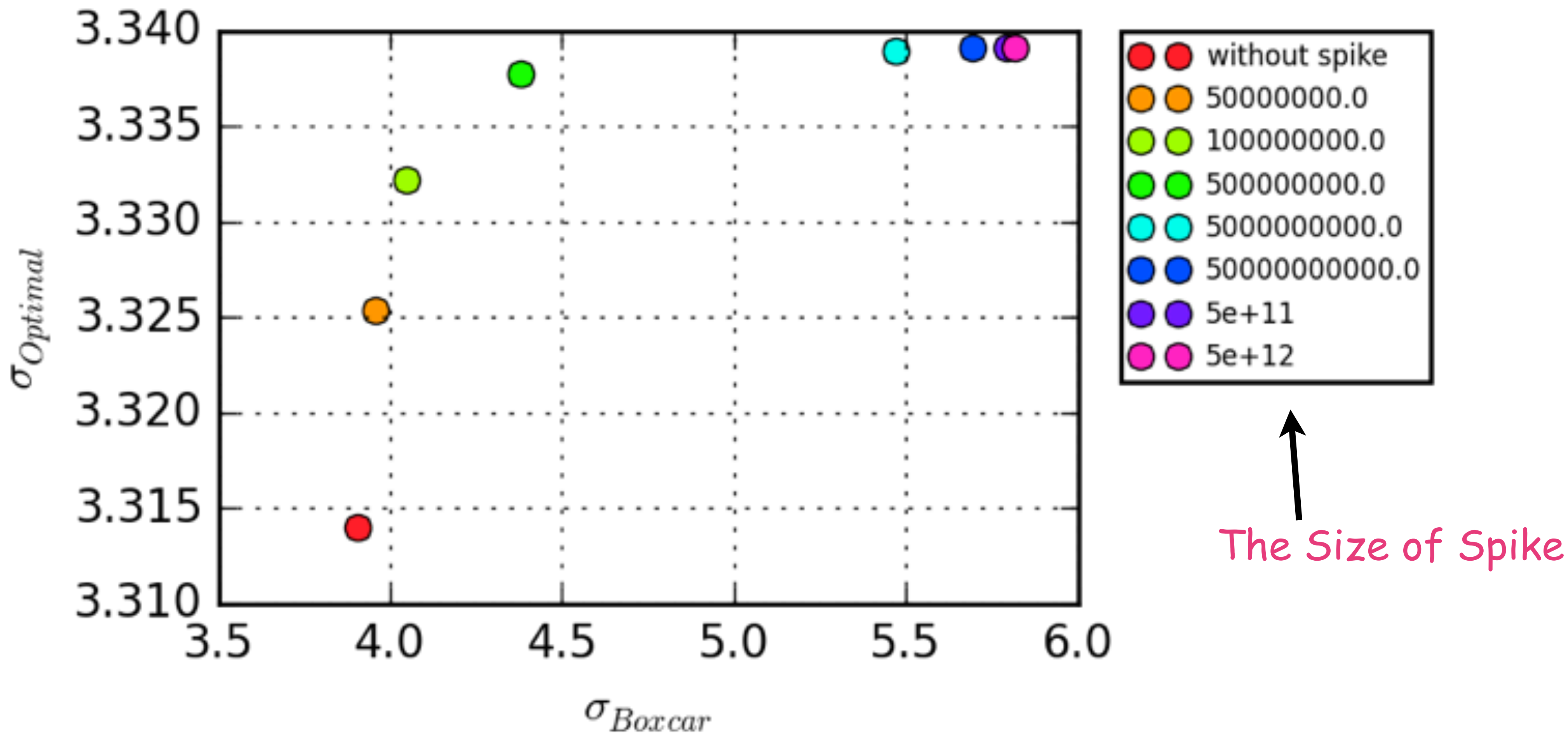


Reoptimized Filters for Different Spike Sizes of T2Z1 Simplified Noise



- Optimal filter simply pulls out the frequency with spike
- Boxcar filter tries to optimize by pushing the bulk of the weight away from the spike

Resolution of Reoptimized Filters for T2Z1 Simplified Noise



Conclusion:

- Optimal filter doesn't get much worse and eventually stops getting worse because we just pull that frequency out
- Boxcar filter gets worse until we push it out

How Robust is the Filter to Noise Changes that Might Occur Over Time

Given Noise $\xrightarrow{\text{calculate}}$ Filter $\xrightarrow[\text{apply}]{}$ Different Noise

Compare resolution

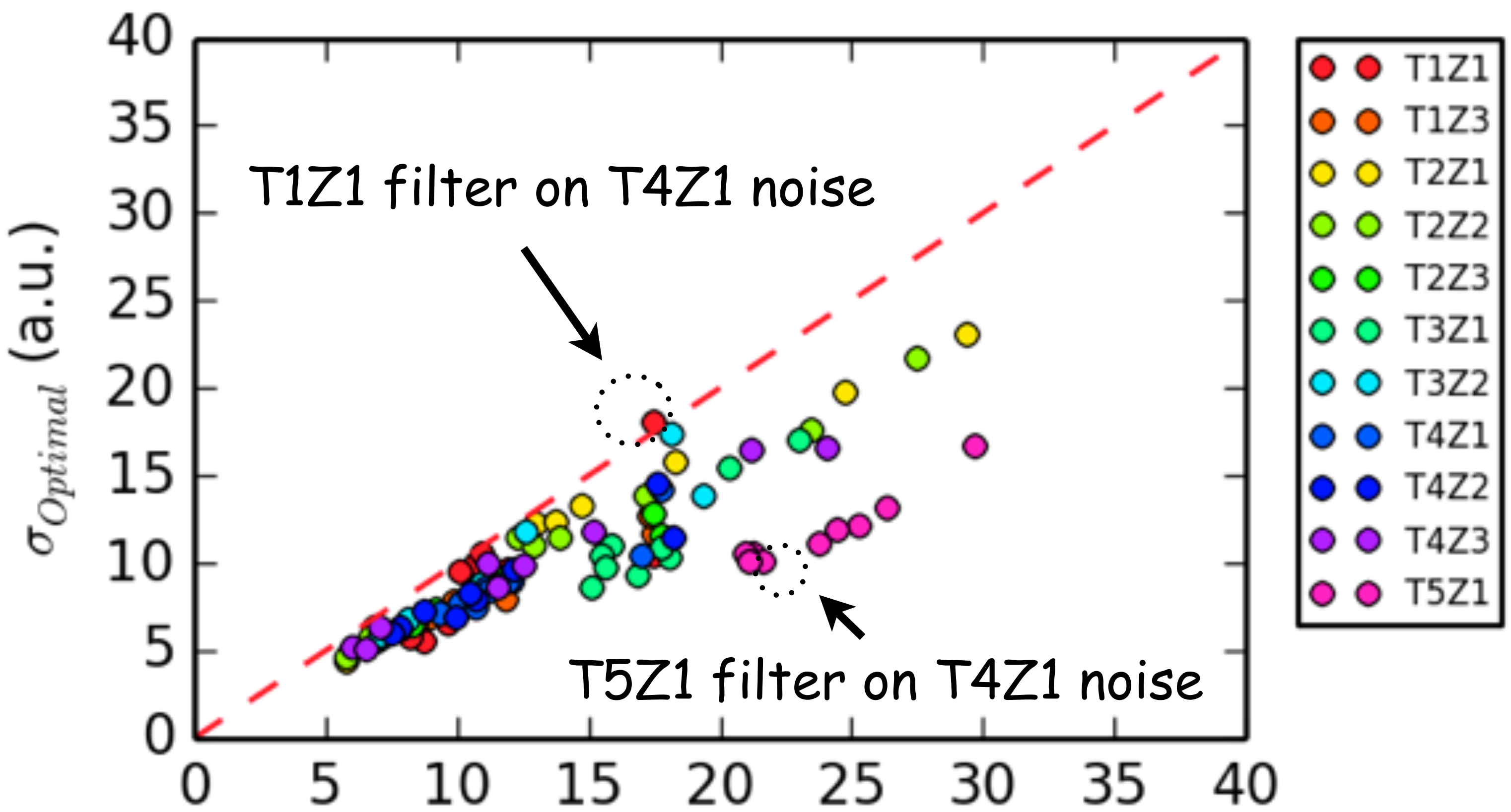
Examine the performance of each filter if the noise for a detector changes

We have 11 detectors and 3 filter options. Run each detector noise through the different filter options and compare.

Apply the Optimal Filter and the Optimized Boxcar Filter on the "wrong noise" simulated by using a different detector

The plot only shows the results for low values of the noise, will show high values in next slide

how well optimal filter works



Most data below red line!

σ_{Boxcar} (a.u.) how well boxcar filter works

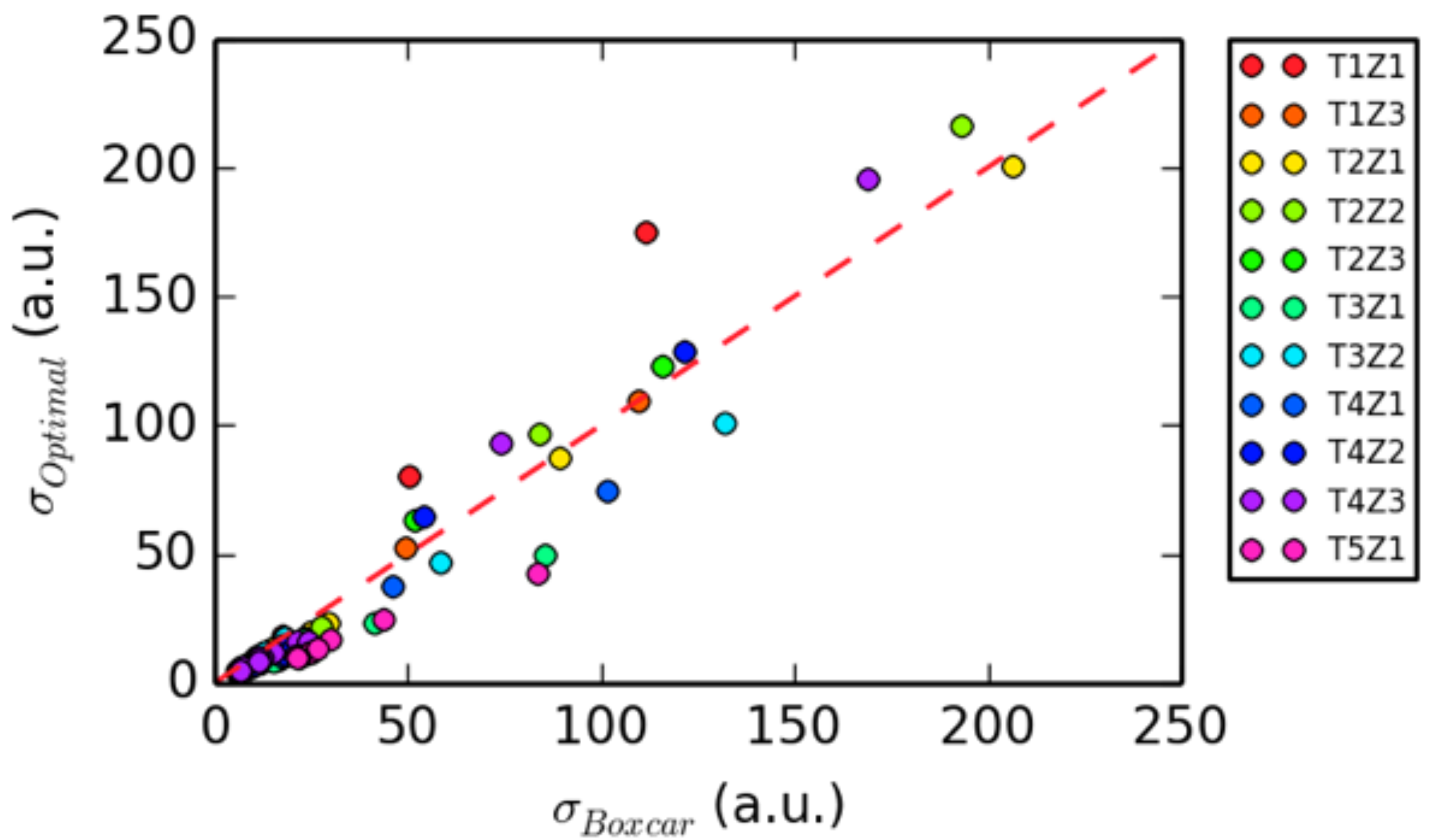
Conclusion:

- Optimal filter works better than boxcar filter in most cases
- Boxcar filter works better than optimal filter in some special cases

What about when there is large noise?

Large Noise Results

When the noise changes a small amount, the optimal filter is still better than the box car filter, this stops being true for large noise

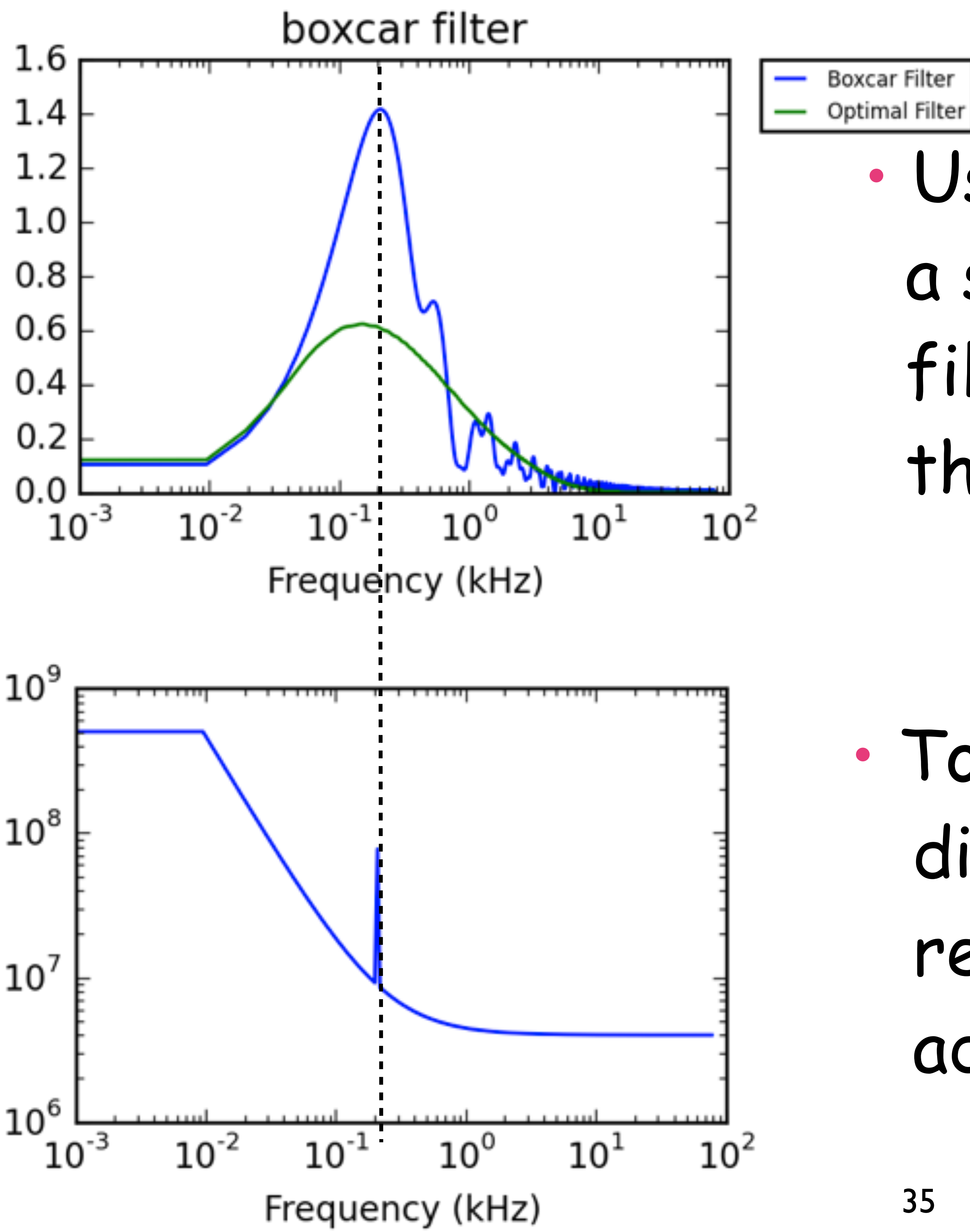


Conclusion:

- For "good" detectors, the optimal filter is more robust than the boxcar filter, but for "bad" detectors, the two seem “equally bad”

Question: What causes the cases where the boxcar starts working better than the optimal filter?

Add a spike in simplified noise of T2Z1

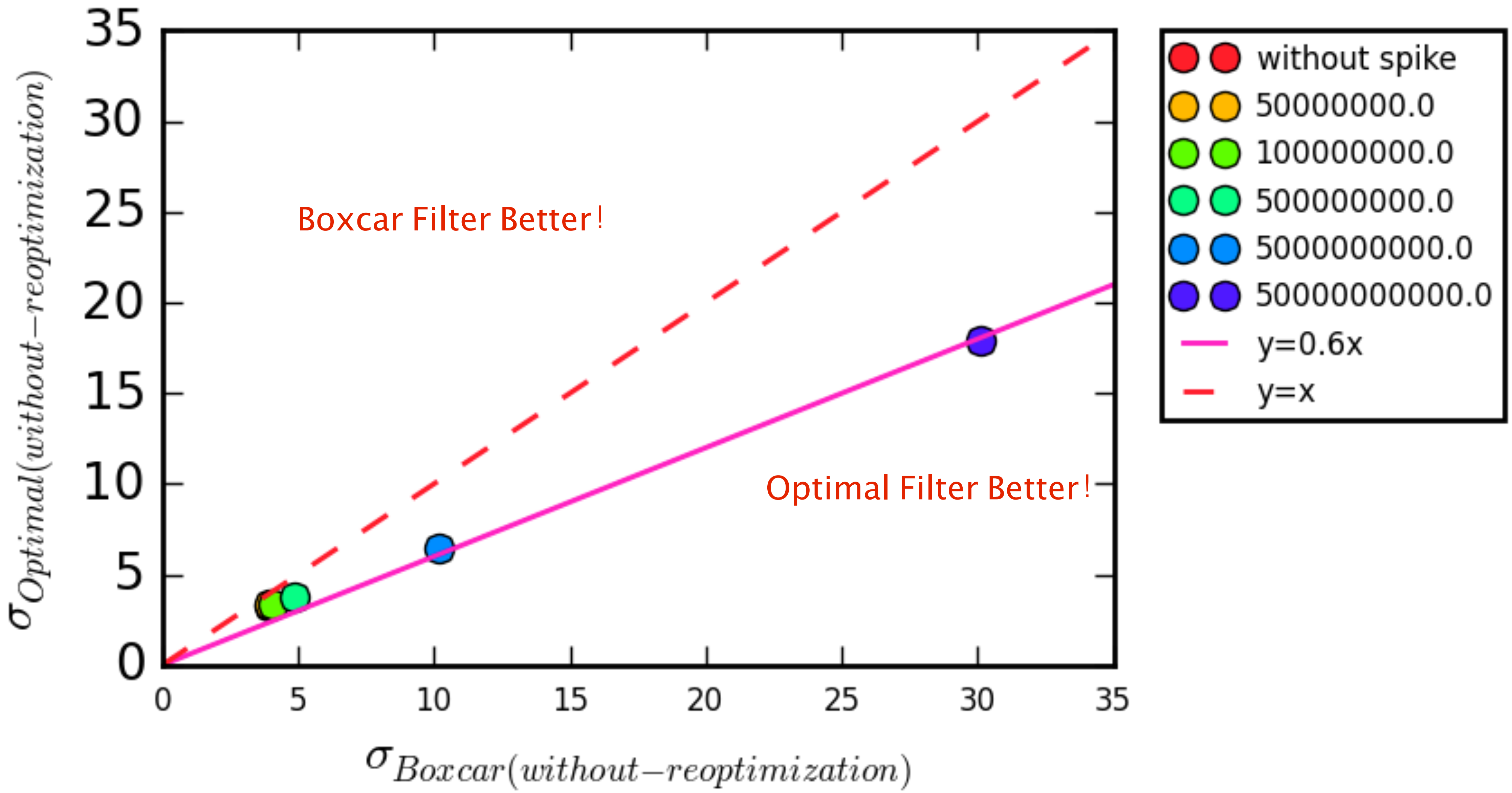


- Use the same model of adding a spike where the boxcar filter weight is larger than the optimal filter weight

Why add spike here?

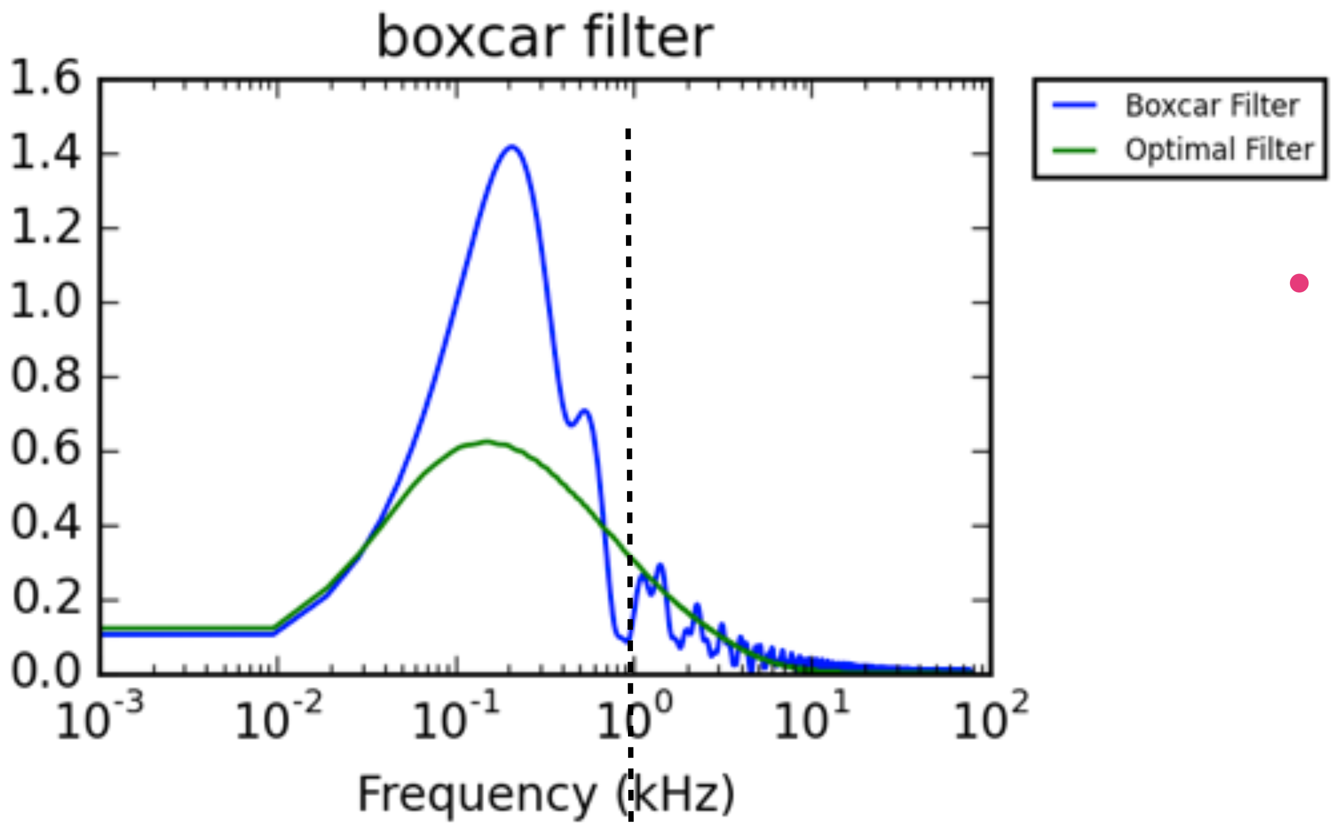
- To see how the weight difference affects the resolution as more noise is added

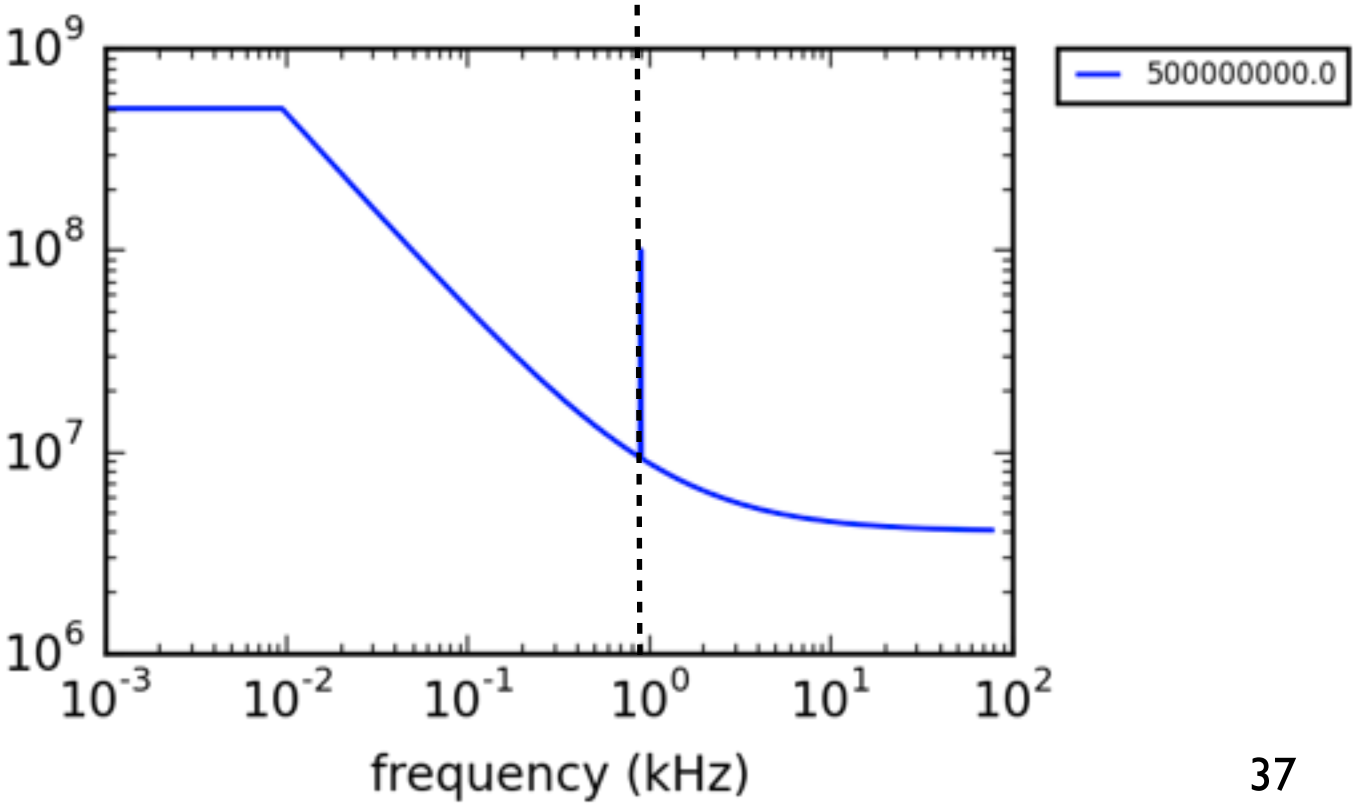
Resolution of Non-reoptimized Filters for T2Z1 Simplified Noise with Spikes



- Both optimal and boxcar get worse when the size of spike increases, but optimal filter is ALWAYS better than boxcar filter

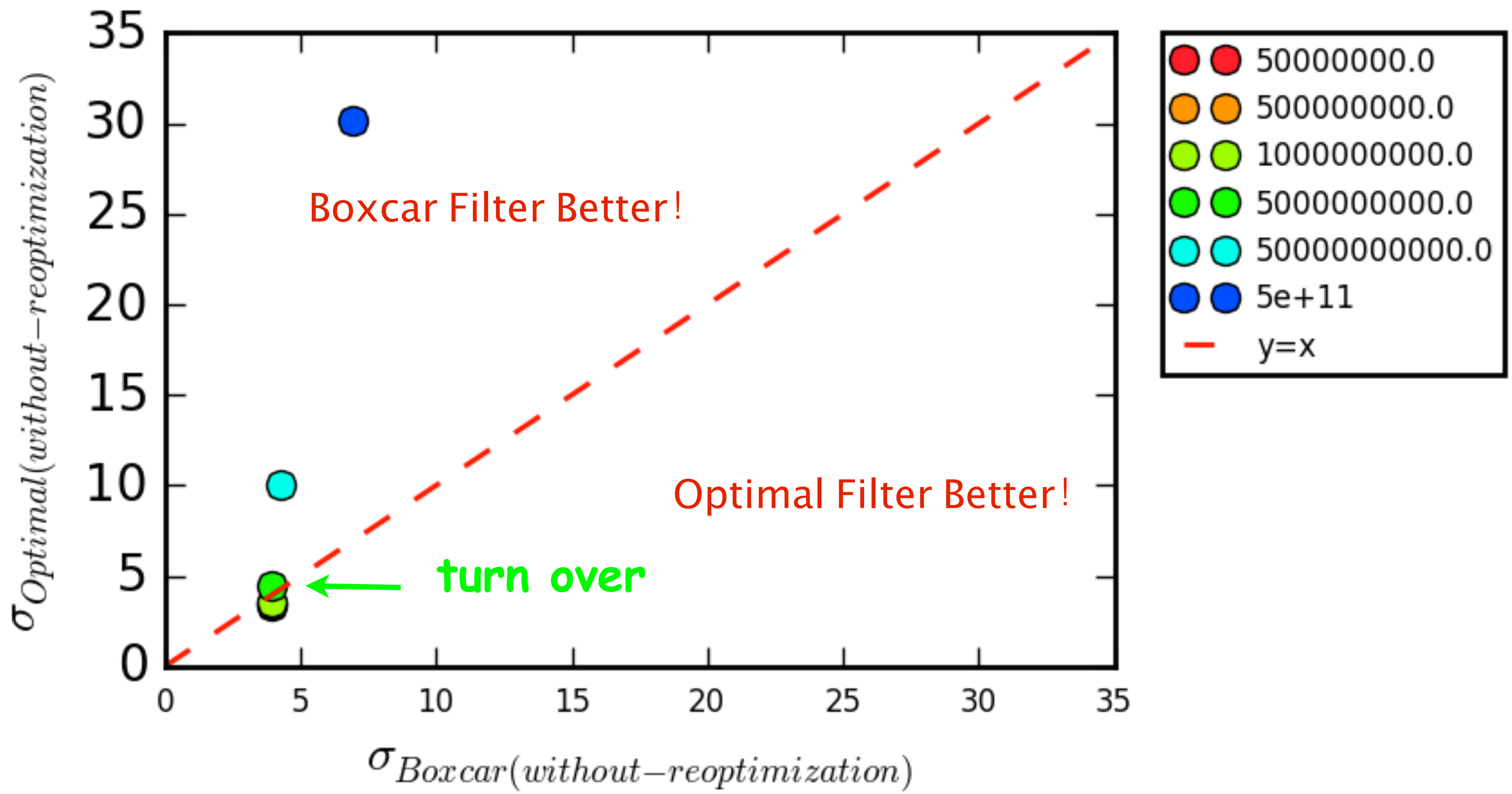
Add a spike at 0.9kHz in simplified noise of T2Z1 Simplified Noise





- Change the spike location to be where the weight of the boxcar filter weight is smaller than the optimal filter weight

Resolution of Non-reoptimized Filters for T2Z1 Simplified Noise with spike at 0.9kHz



- As expected, the optimal filter works better than the boxcar filter for noise with a small spike, but as the spike gets bigger, eventually the boxcar filter becomes the better filter

Conclusions

- We are searching for dark matter with the CDMS experiment, and upgrading the experiment and trigger for use at the SNOLAB mine.

- The sensitivity of the filter choice in Level 1 is a key to CDMS's ability to discover dark matter

- We have studied the use of an optimal filter, a boxcar filter and a bandpass filter, and found that the optimal filter always works better by approximately 15% to 50%

- Our studies suggest that we need to be vigilant in monitoring the noise in the detector over time as it can quickly make us non-optimal and make the resolution/search sensitivity much worse

- Hopefully with high quality triggering and monitoring we will discover dark matter soon

Thank you !

&

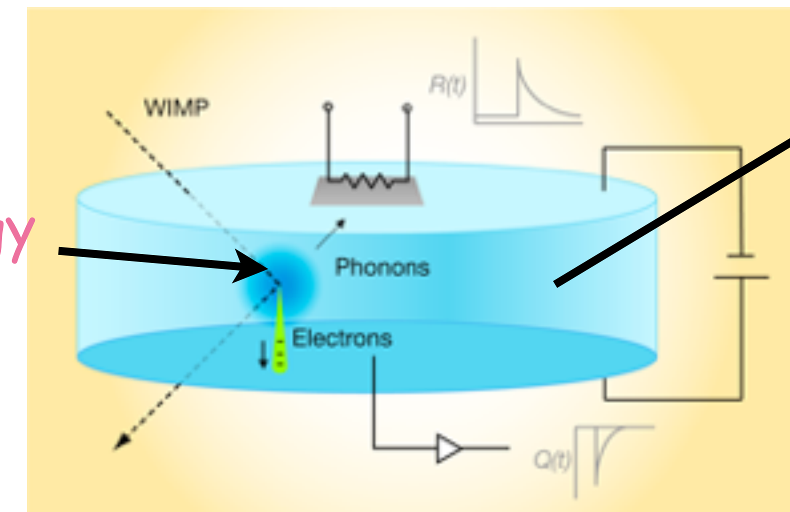
Special thanks to my committee members:

Drs. Almes, Dutta and Toback

Back-up slides

CDMS Pulse Read Out

Detector

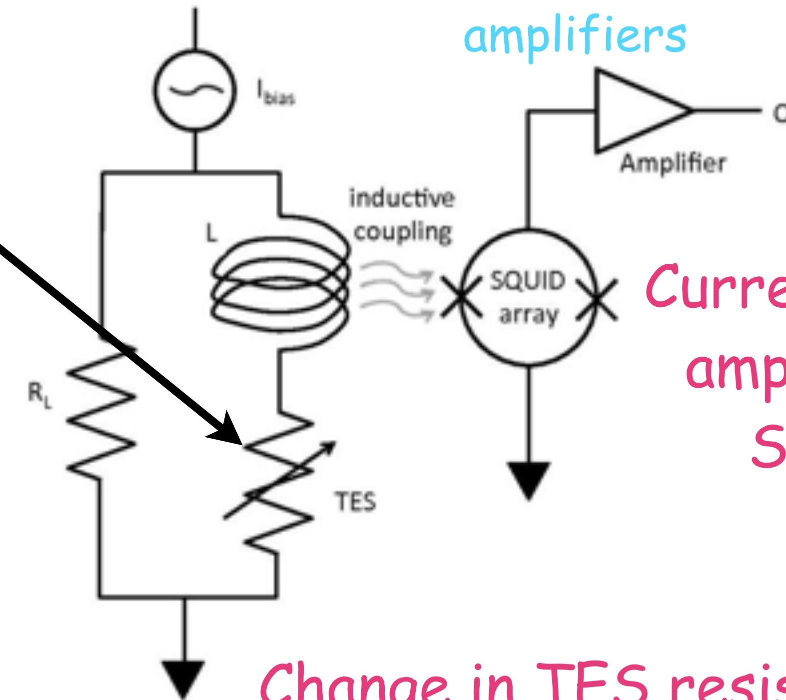


Energy

Phonon
(crystal vibration)

Series amplifiers

Pulse read out

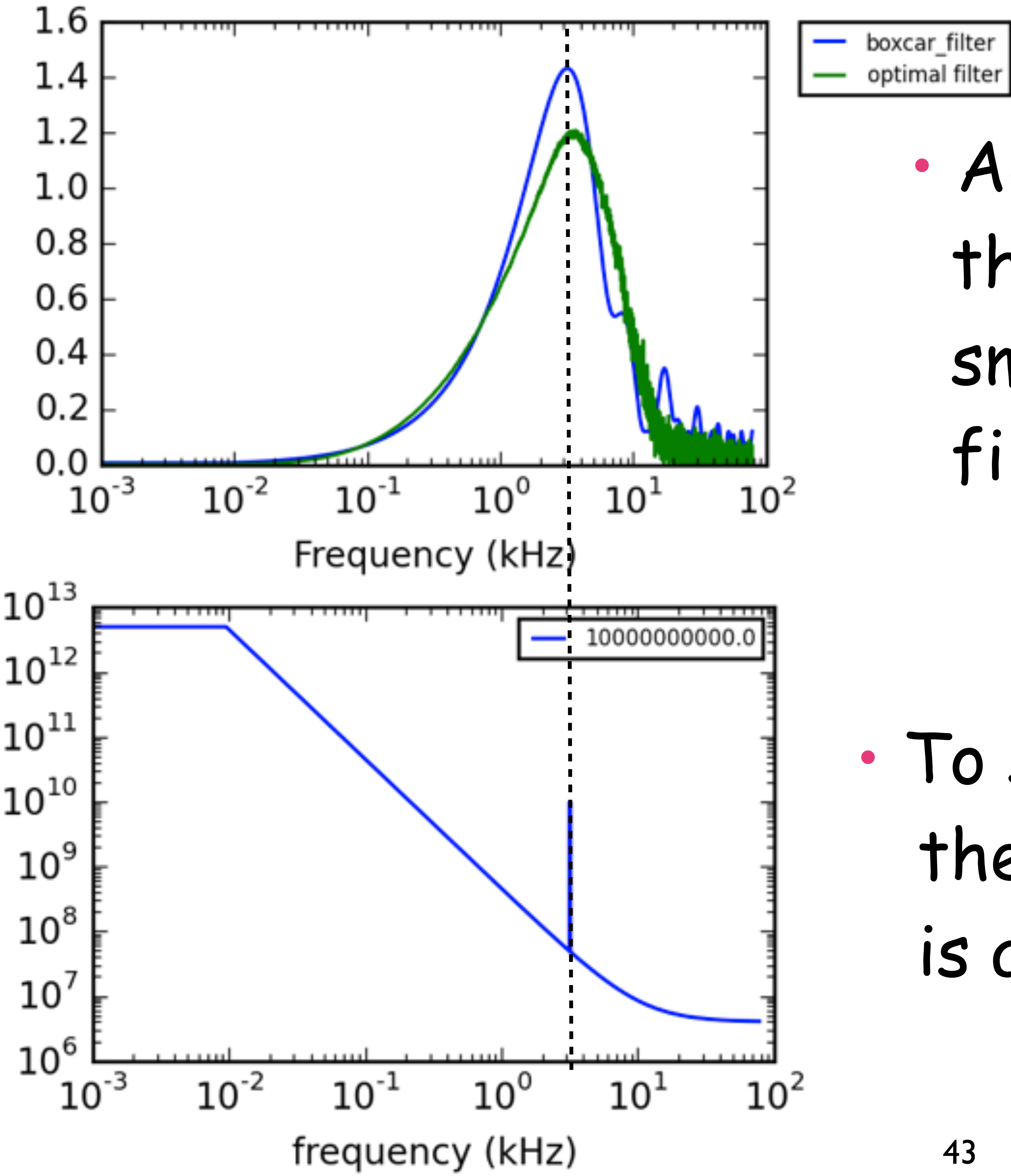


Current change amplified by SQUID

Change in TES resistance
→current change

- TES = Transition Edge Sensor
  (exploit their transition from superconducting to normal as a way to sense a small input of energy)
- SQUID = Superconducting Quantum Interference Device (amplifier)

Add a spike in simplified noise of T5Z1

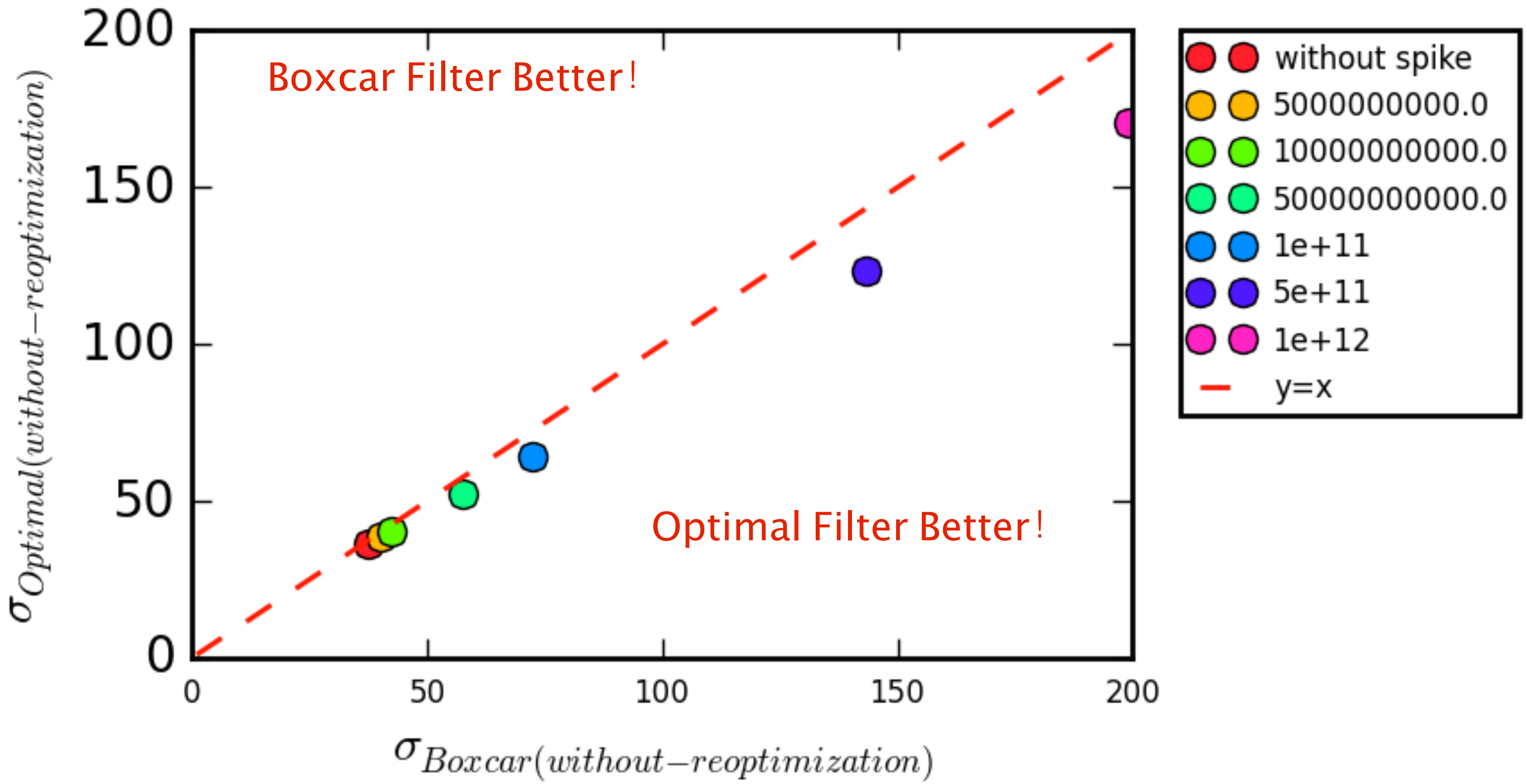


- Add the spike at where the optimal filter weight is smaller than the boxcar filter weight

Why add spike here?

- To see how the weight affects the resolution as more noise is added there

Resolution of Non-reoptimized Filters for T5Z1 Simplified Noise



- Both optimal and boxcar get worse when the size of spike increases, but optimal filter is ALWAYS better than boxcar filter

How to Calculate Optimal Filter ?

- Estimate the amplitude of a signal of known shape A(t) amidst a background of gaussian random noise of known power spectral density (PSD) J(f)
- Signal traces S(t)= aA(t) + n(t) ← Estimate a

  A(t) - known template

  n(t) - noise realization with J(f)=<n(f)>

Optimal technique for amplitude estimation: perform a frequency-domain ChiSquare:

$$\chi^2(a) = \sum_n \frac{\left|\tilde{S}_n - a\tilde{A}_n\right|^2}{J_n}.$$

Minimize it →

$$\hat{a} = \frac{\sum_n \frac{\tilde{A}_n^* \tilde{S}_n}{J_n}}{\sum_n \frac{|\tilde{A}_n|^2}{J_n}}.$$

The estimate of a