Results of the Hardware Injections performed on the LIGO Interferometers

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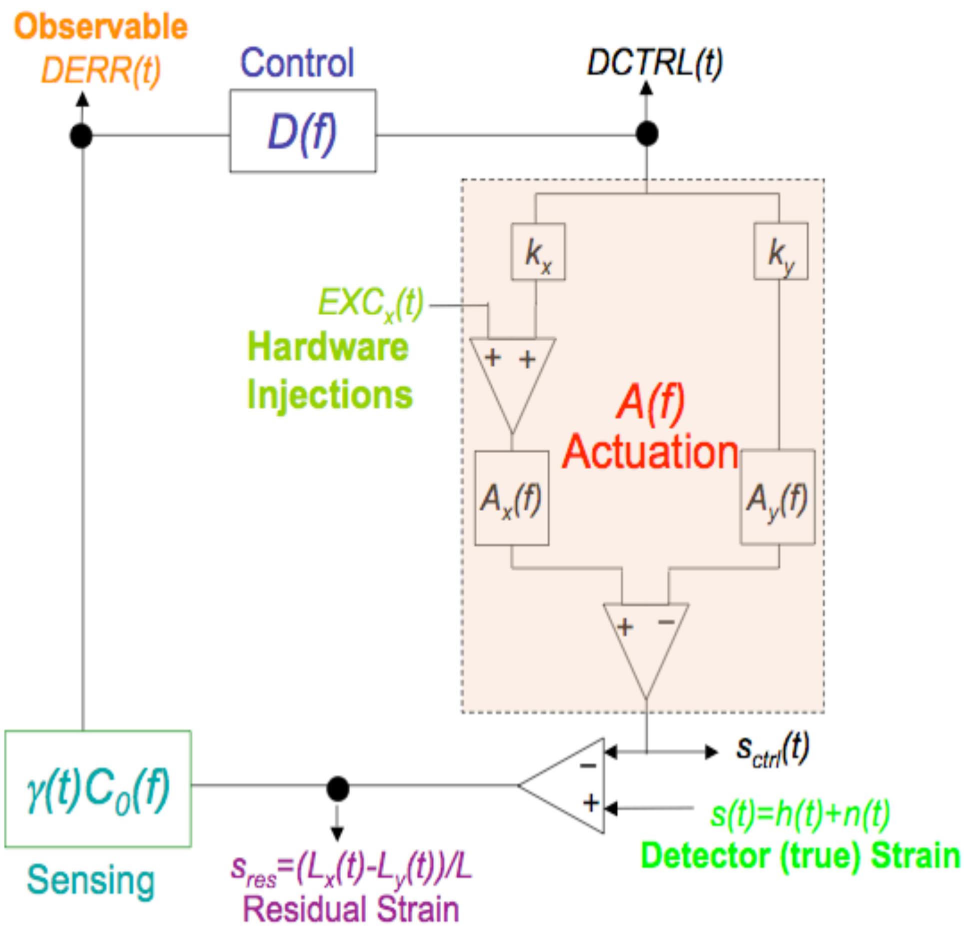
LIGO Hardware Injections

- Hardware injections are the only direct test of detector time response.
  - Detector deforms gravitational waveform in a predictable (?) way.
  - Detector response function quantifies this deformation.
- Injections are also a good test for measuring the absolute size of signal.
- Hardware injections on the S5 run of LIGO
  - Burst/Inspiral injections, pulsar injections, stochastic injections, special injections.
  - Very little dead time - <0.5% of livetime due to burst/inspiral injections
- Analysis consists of successive application of linear filters on raw data (error signal):
  - Whitening filters, applied once and twice.
  - *Transformed* template (from strain to error signal)
- Diagnostic tool with prompt analysis after each injections.
- KleineWelle analysis of veto safety of auxiliary data channels

Servo Diagram of IFO



- Infer strain $s(f)$ from observable $DERR(f)$:

$$s(f) = R(f)DERR(f)$$

- Calibration team measures this detector response function $R(t,f)$:

$$R(t,f) = \frac{1+\gamma(t)G_0(f)}{\gamma(t)C_0(f)}$$

where open loop gain $G_0(f)$:

$$G_0(f) = D(f)A(f)C_0(f)$$

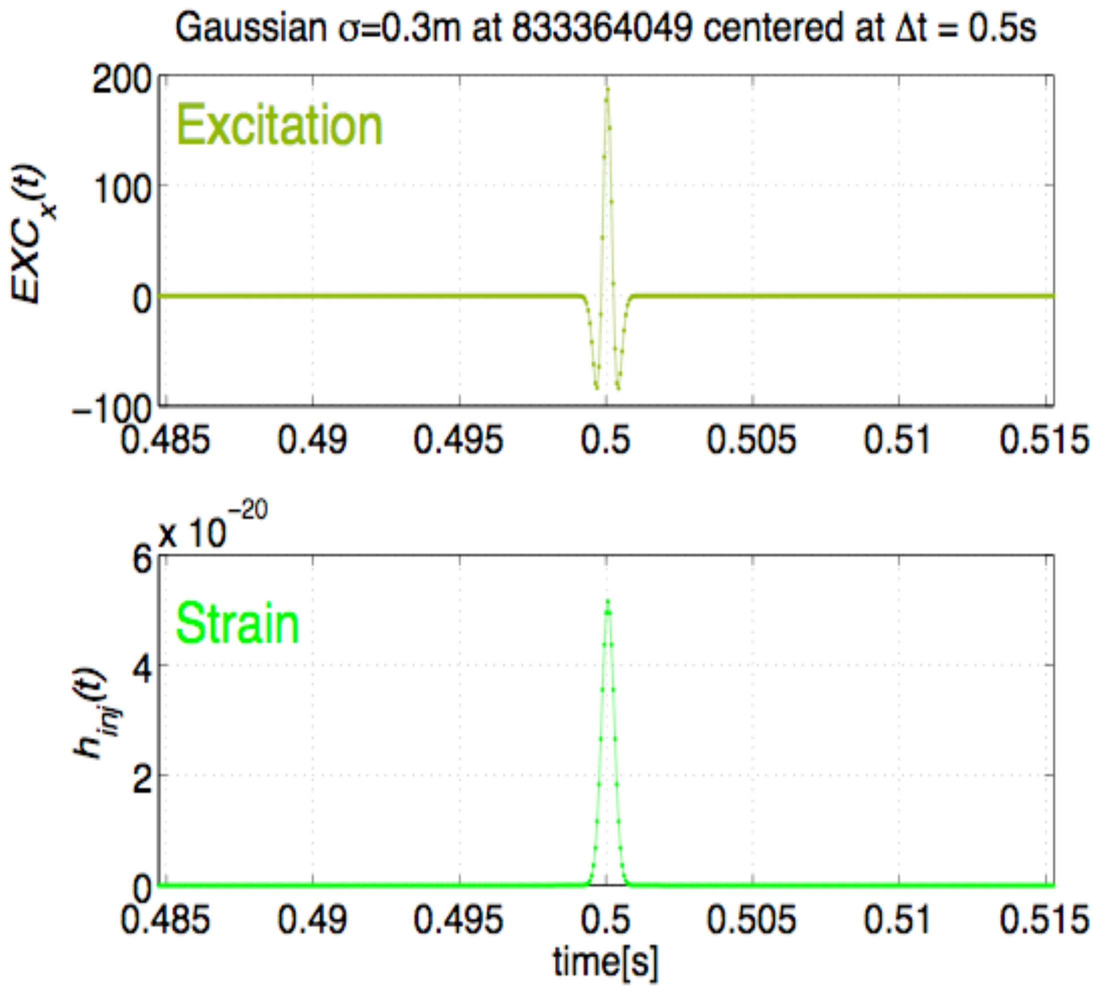
- $EXC_x(t)$ for hardware injections:

$$EXC_x(f) = -h_{inj}(f)/ A_x(f)$$

Burst Injections

- Twenty different burst waveforms in strain, *h(t)*
  - Four Gaussians: σ = 0.3, 1.0, 3.0, 10 ms.
  - Sine-Gaussians (Q=9) with 12 frequencies from 50Hz to 3068Hz
  - Supernova waveform: Zwerger-Mueller (A3B3G1)
  - Cosmic string - cusp (f_{cutoff} = 220Hz)
  - Band-limited white noise burst: f = 250Hz, δf = 100Hz and σ = 30ms
  - Ringdown: f = 2600Hz δt = 30ms
- Various settings of strengths and time for each injections
  - Same waveform injected to three IFOs with time shifts (if in science mode).
  - Two regular injections daily on average, each with three waveforms.
  - Loud injections of Gaussians and sine-Gaussian at least once per week for studying coupling to auxiliary channels and impulse response of detector.

Gaussian (σ = 0.3ms) injection



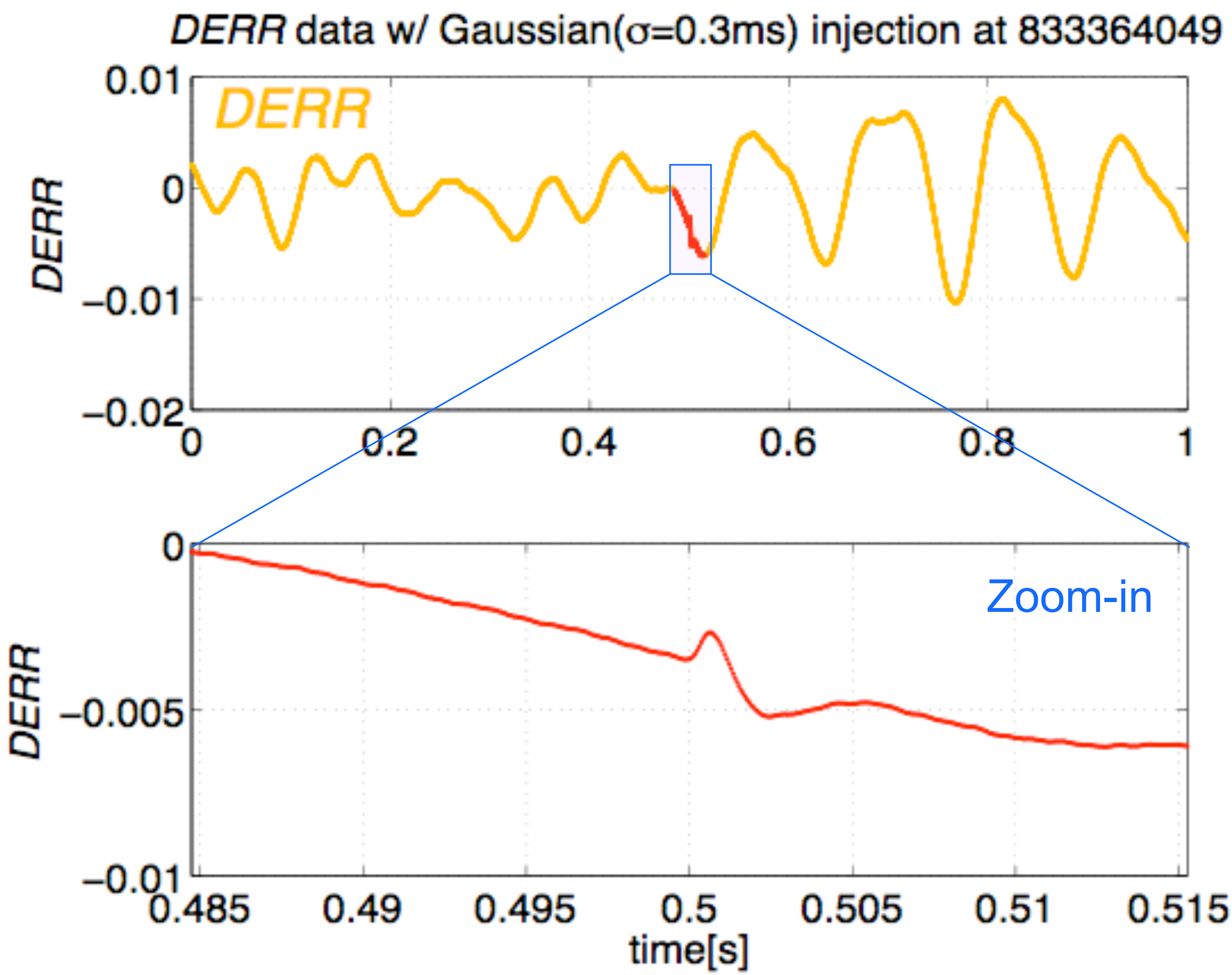
- Use actuation function, $A_x(f)$, to calculate the excitation function: $EXC_x(f)$

$$EXC_x(f) = -h_{inj}(f) / A_x(f)$$

- Note: this injection is approximately an *impulse* in strain.

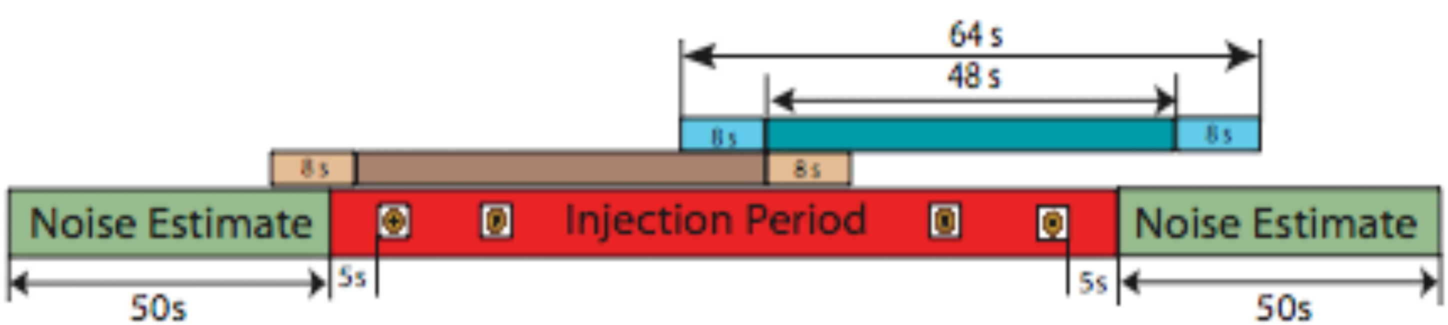
Result of injection

or impulse response

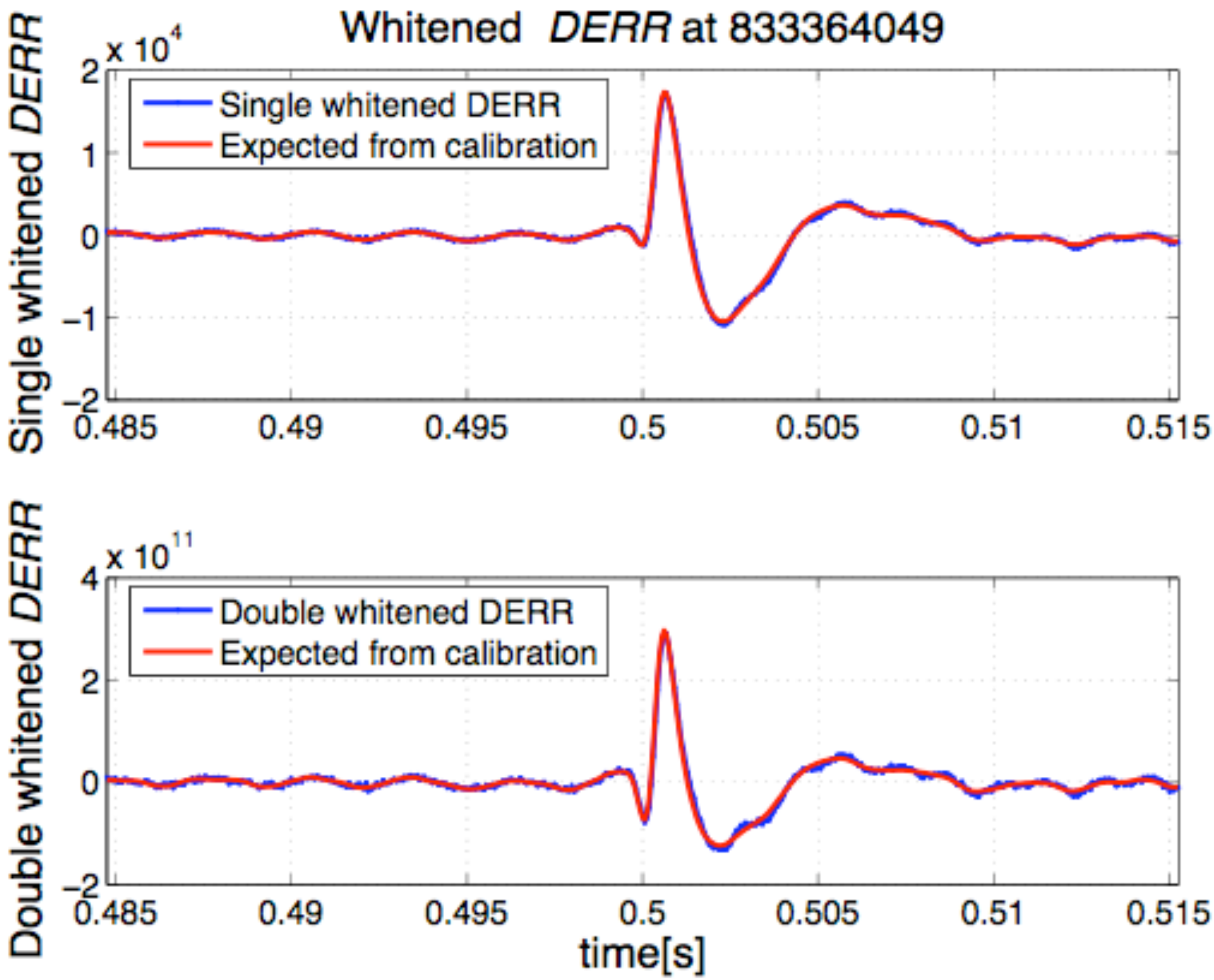


Analyzing Injection Data

- Matlab scripts (python scripts for controlling jobs)
- Use *DERR(t)* data
- Time windows of 64s, Tukey windowing to use the middle 48s
- Whitening filters
  - Single whitening filter: $sw(t) = \int_0^\infty \frac{derr(f)}{\sqrt{S(f)}} e^{-2\pi i f t} df$
  - Double whitening filter: $dw(t) = \int_0^\infty \frac{derr(f)}{S(f)} e^{-2\pi i f t} df$
  - Noise estimate, *S(f)*, from two 50s long data before and after injection period.



Whitened *DERR*
or whitened impulse response



Optimal Linear Filter

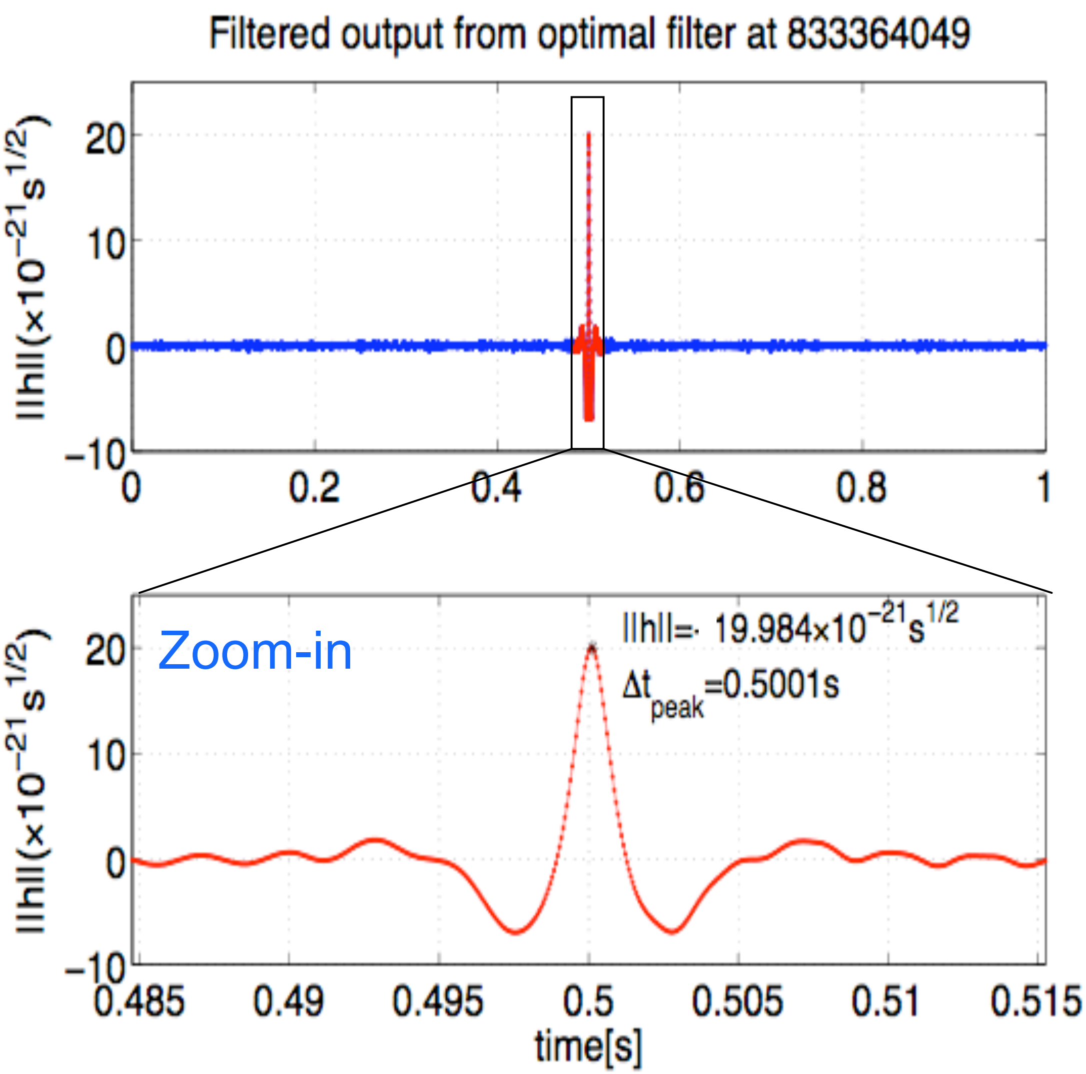
$$||h(t)|| = N_\alpha \int_0^\infty \frac{d_\alpha^*(f) derr(f)}{S(f)} e^{-2\pi i f t} df$$

- A standard method from classical signal processing.
- Matched filter study: template from injected waveforms with the detector response function (Calibration):

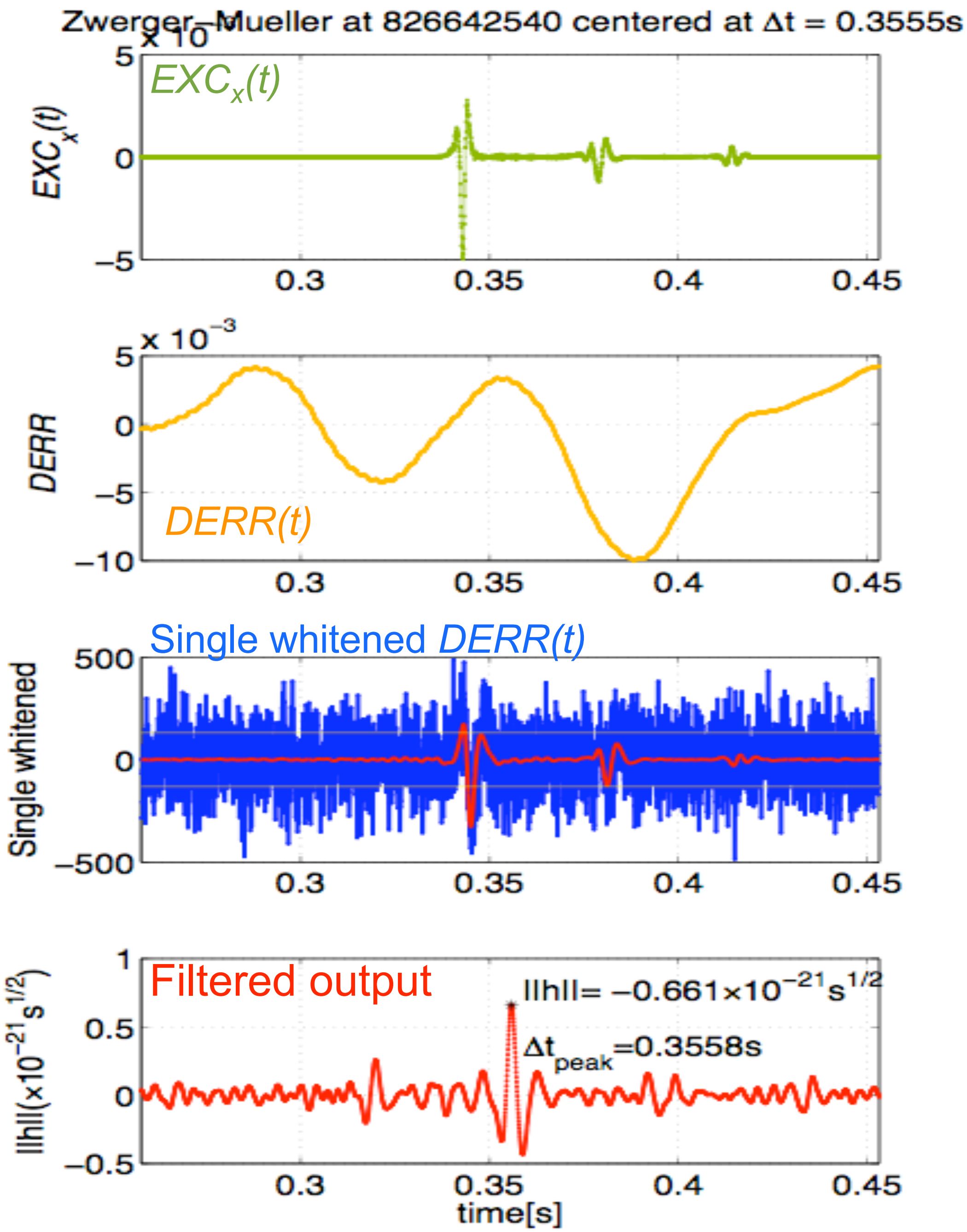
  $d_\alpha(f) = h_{inj}(f) / R(f)$

- Optimized for the measured stationary noise of detector - Double whitening.
- It is also a *linear* measure of the strength;
  - Choose normalization so ||h|| is unbiased estimate of true h_{rss} of this waveform.
  - Response functions cancel , i.e., the equivalent expressions for either observable *DERR(t)* or strain *s(t).*

Filtered output from loud Gaussian



- Strength Measurement
  - Injected: $20\times 10^{-21}s^{1/2}$
  - Measured: $19.984\times 10^{-21}s^{1/2}$
  - rms(noise): $0.0357\times 10^{-21}s^{1/2}$
- Time measurement
  - Injected time offset: 0.5 s
  - Measured time offset: 0.5001s

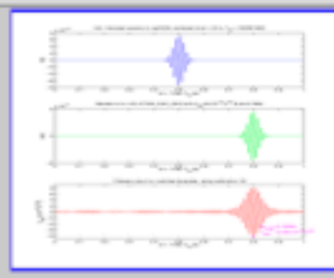
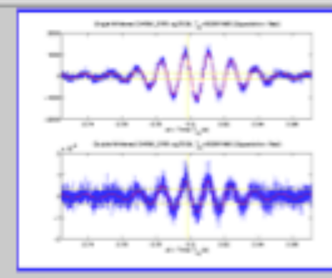
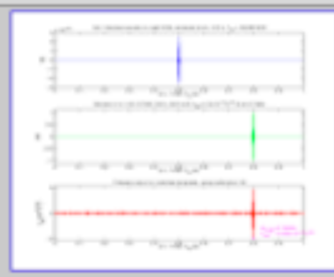
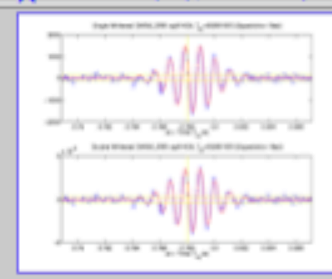
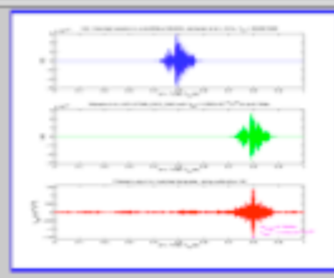
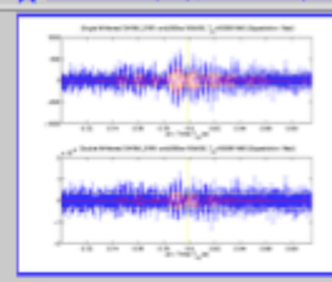


Supernova waveform: Zwerger-Mueller (A3B3G1)

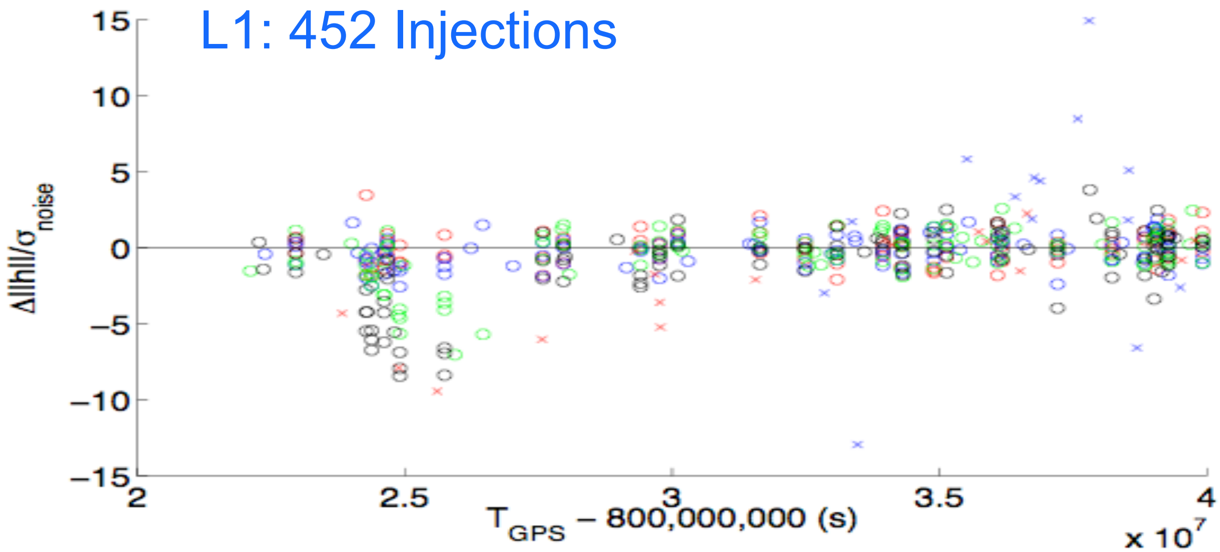
- Strength Measurement
  - Injected: $0.6\times10^{-21}s^{1/2}$
  - Measured: $0.661\times10^{-21}s^{1/2}$
  - rms(noise): $0.04168\times10^{-21}s^{1/2}$
- Time Measurement
  - Injected offset: 0.3555s
  - Measured offset: 0.3558s

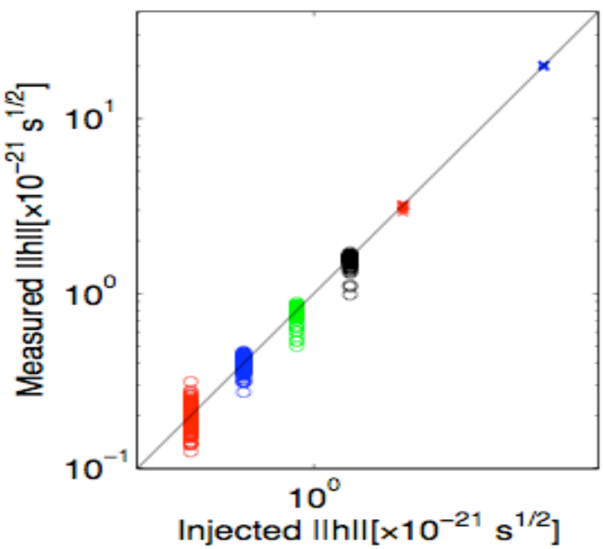
Hardware injection monitoring

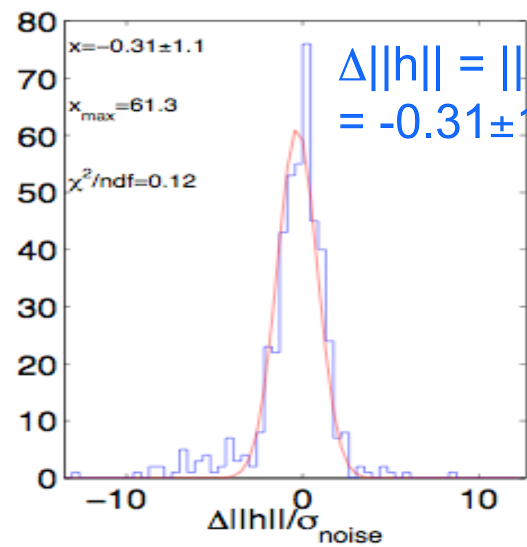
- snapshot of online display for scimons -

Intended Injection Parameters	Resulting Waveforms	Results $\epsilon_h \equiv (hrss_{expected} - \|hrss_{peak}\|)/\sigma_{noise}$ σ_{noise}: rms(noise)	Direct Response (DARM_ERR whitened)
T_{inj}=832561960 Sine-Gaussian f=70Hz Q=9 t_{offset}=0.798 s hrss=8×10^{-21} $s^{1/2}$		$hrss_{peak}$ = -8.292×10^{-21} $s^{1/2}$ ϵ_h=-5.243, σ=5.560e-23 $s^{1/2}$ Δt_{peak} = 0.7980 s $\delta(\Delta t)$=-0.0000 s Mismatched Filter Study	 χ^2=0.874915(sw), 0.859358(dw)
T_{inj}=832561970 Sine-Gaussian f=914Hz Q=9 t_{offset}=0.798 s hrss=4.8×10^{-21} $s^{1/2}$		$hrss_{peak}$ = -4.809×10^{-21} $s^{1/2}$ ϵ_h=-0.106, σ=8.468e-23 $s^{1/2}$ Δt_{peak} = 0.7980 s $\delta(\Delta t)$=-0.0000 s Mismatched Filter Study	 χ^2=1.720755(sw), 1.665454(dw)
T_{inj}=832561980 Band-Limited White Noise Burst f=250hz δf=100hz σ=30ms t_{offset}=0.798 s hrss=1.4762×10^{-21} $s^{1/2}$		$hrss_{peak}$ = -1.474×10^{-21} $s^{1/2}$ ϵ_h=0.092, σ=2.803e-23 $s^{1/2}$ Δt_{peak} = 0.7980 s $\delta(\Delta t)$=-0.0000 s Mismatched Filter Study	 χ^2=1.060200(sw), 0.962461(dw)

Gaussian σ=1ms: Strength Measurement

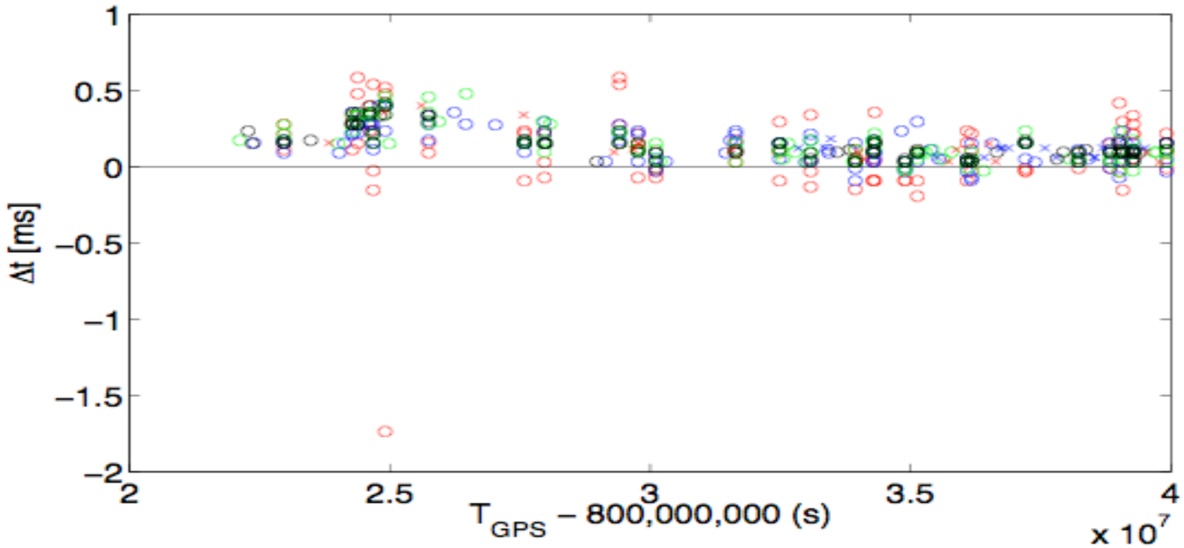


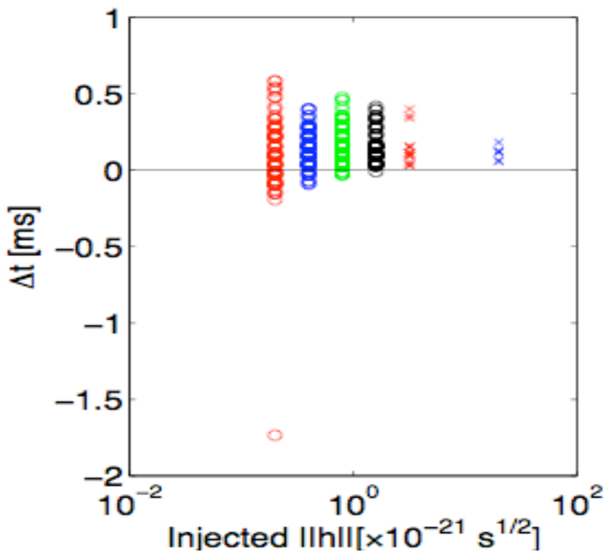


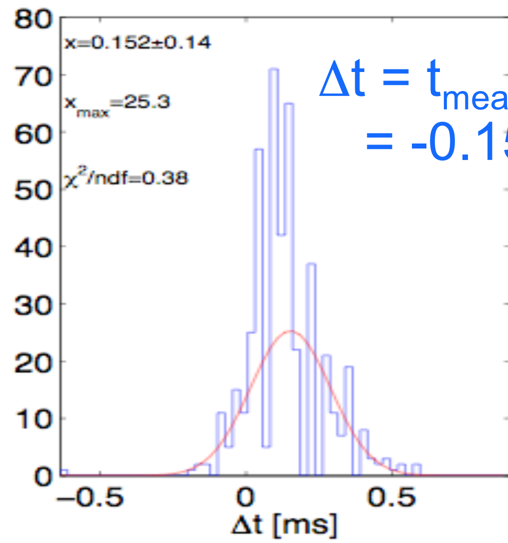


$\Delta||h|| = ||h||_{measured} - ||h||_{injected}$
$= -0.31 \pm 1.1$ rms(noise)

Gaussian σ=1ms: Time Measurement



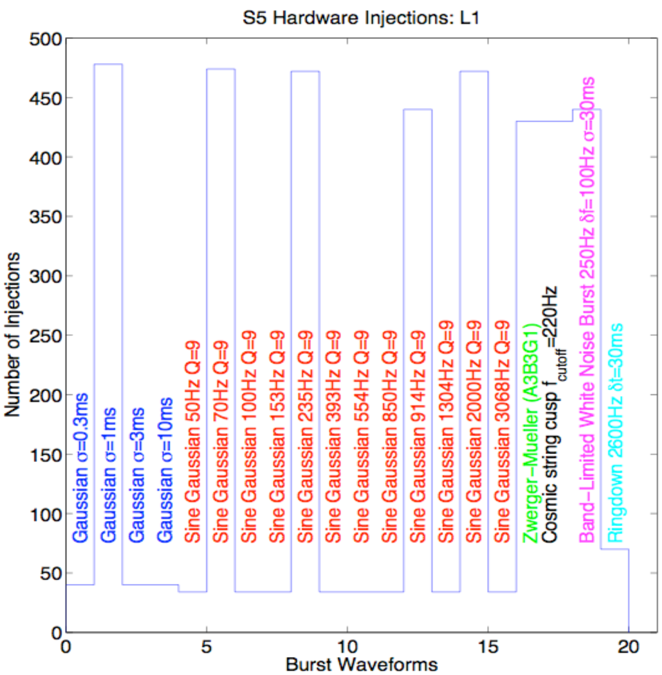


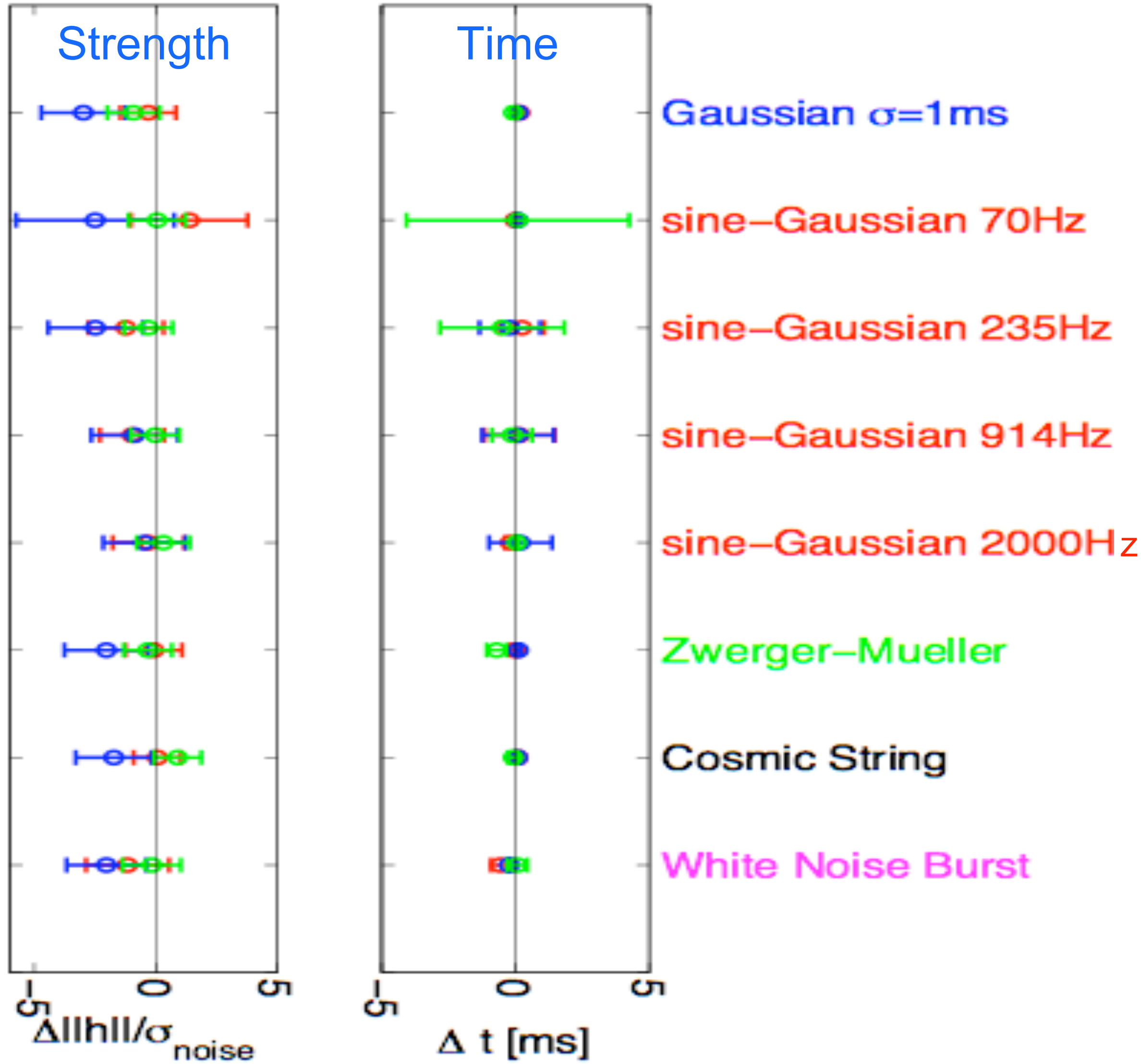


$\Delta t = t_{measured} - t_{injected}$
$= -0.15 \pm 0.14$ ms

Measuring Burst Injections

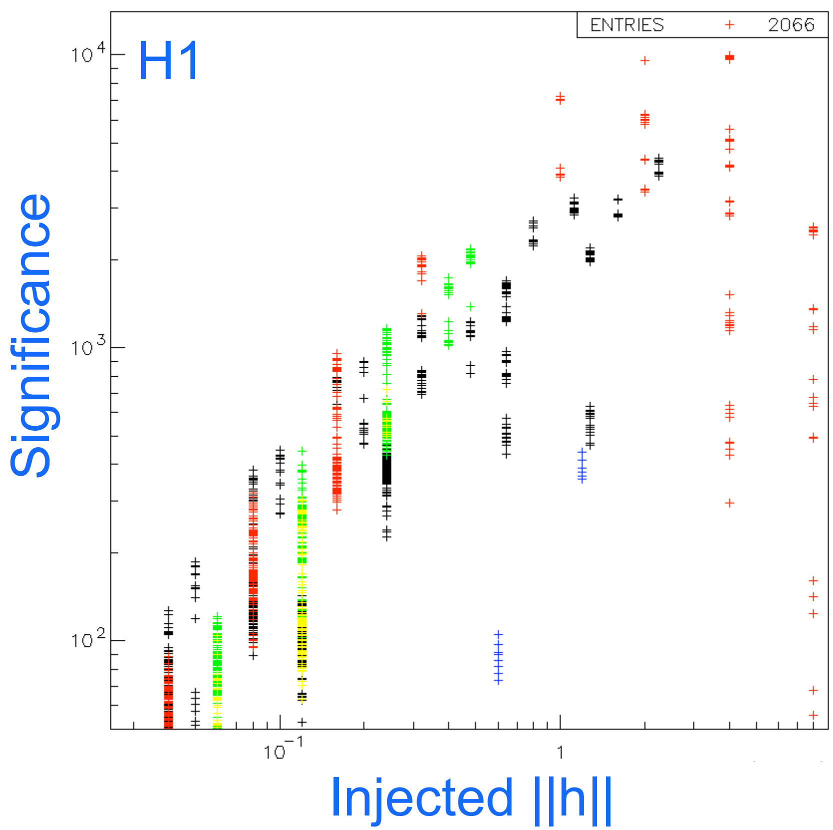
- Jan. 19 - Aug. 23, 2006
- Number of injections:
  - H1 - 5018
  - H2 - 5958
  - L1 - 4098

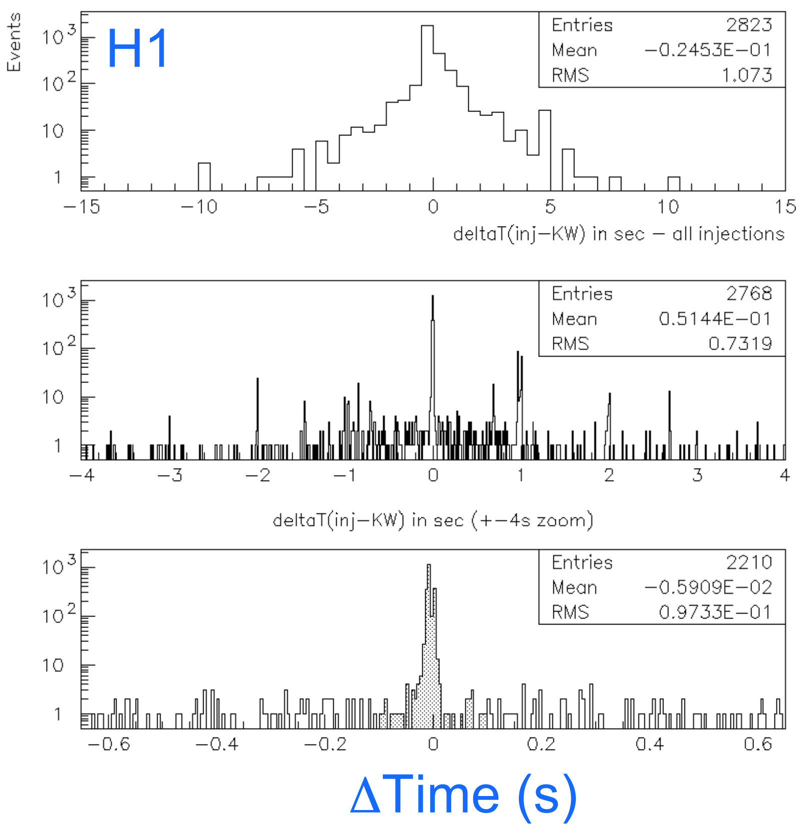




Veto Safety Study using Hardware Injection

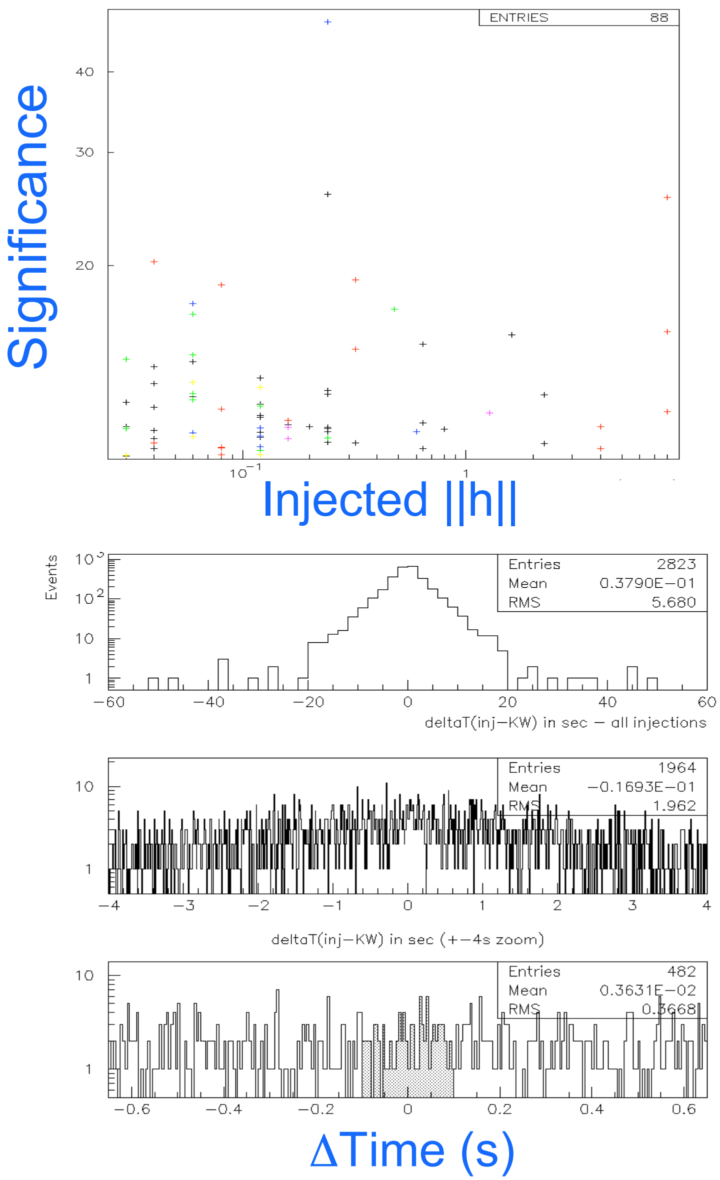
- Transients identified by KleineWelle algorithm on auxiliary data channels at the time of injections
- Injections from 272 days of S5 run
- From *DERR*:



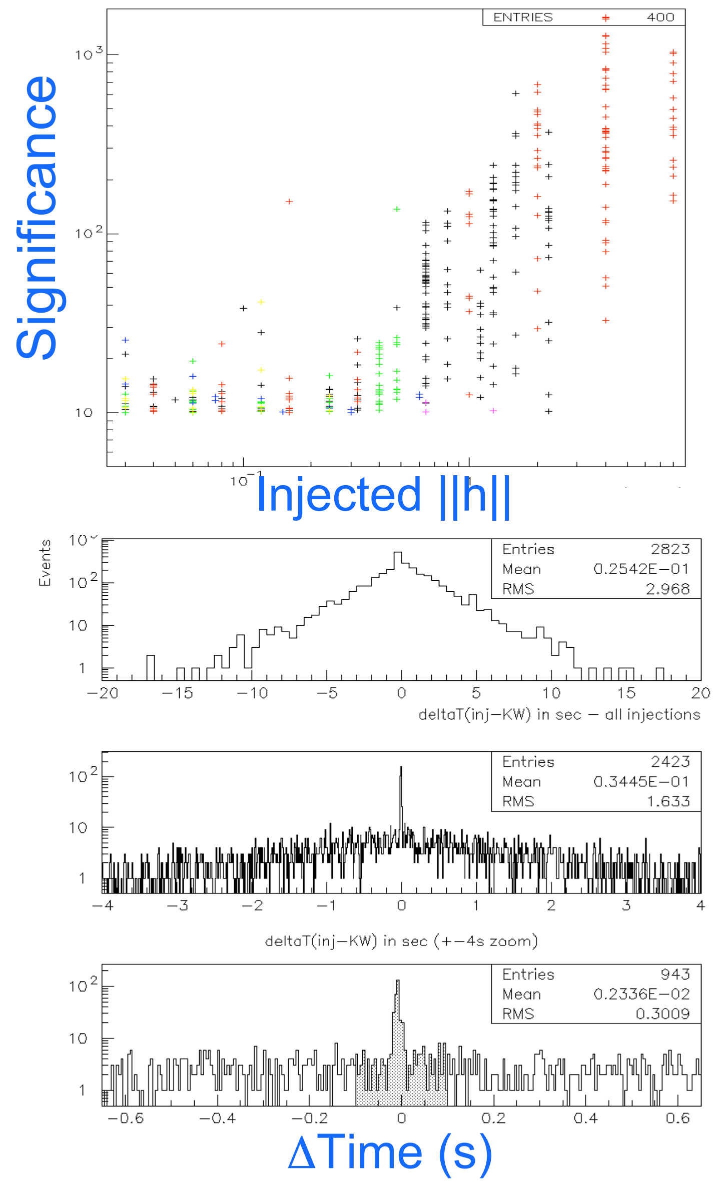


Veto Safety Study using Hardware Injection

- *RMP(Recycling Mirror Pitch)* - Safe



- *ASI(Antisymmetric port In-Phase)* - Unsafe



Summary

- Hardware injection provides very useful tools to understand the performance of interferometers.
- Injections during S5 are analyzed by using
  - Whitening filters
  - Optimal linear filters
  - KleineWelle algorithm
- Prompt result from hardware injections is available and used as a diagnosis tool.
- From statistical study, detector response to injected waveforms is analyzed.
- Veto safety study on auxiliary data channels with transients from KleineWelle algorithm.